EPA/600/R-97/048
September 1997

Developing and Using Production-Adjusted Measurements of Pollution Prevention

by

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Cooperative Agreement No. CR 823018

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Notice

The U.S. Environmental Protection Agency through its Office of Research and Development partially funded and collaborated in the research described here under Cooperative Agreement No. CR 823018 to the National Risk Management Laboratory. It has been subjected to the Agency's peer and administrative review and has been approved for publication as an EPA document.

Foreword

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

Abstract

This report describes research examining production-adjusted measures of pollution prevention (P2). Under this research, a methodology was developed for applying statistical and graphical tools to assess the accuracy of the factors (called units-of-product) used to adjust P2 measures. Graphical analysis is used to qualitatively assess a unit-of-product, while regression analysis is used to quantitatively evaluate a unit-of-product. Researchers applied these statistical and graphical tools to data from five case study facilities in different industrial sectors. The units-of-product currently being used by the facilities were tested for correlation with key waste or chemical use streams. It was found that the methodology for applying statistical and graphical tools was usable with data routinely collected at the five case study facilities. Researchers further found that the factors being used by four of the facilities correlate with chemical usage for key input streams. This result indicates that these factors accounted for enough of the variation in production that the factors could be used for accurate production-adjusted P2 measurement. Data analysis from a fifth facility underlined the challenges of obtaining data appropriate to the methodology, and conclusions were not drawn about the unit-of-product used by that facility.

This report was submitted in fulfillment of Cooperative Agreement Number CR 823018 by Research Triangle Institute and Greiner Environmental under the sponsorship of the United States Environmental Protection Agency. This report covers a period from February 15, 1995, to December 30, 1996, and was completed as of February 11, 1997.

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Executive Summary

ES.1 Introduction

Accurate and meaningful measurement systems are essential to the long-term success of pollution prevention (P2) in industrial settings. As companies move beyond short-payback P2 projects to longer-term, capital-intensive P2 activities, corporate management will rightly demand accounting of the environmental and cost benefits of these projects. In addition, many regulatory bodies and community groups are beginning to ask individual facilities to demonstrate that they are making progress in improving environmental performance. Credible methods of measuring P2 are key elements in any of these requirements.

Accounting for varying levels of production is one of the key issues in P2 measurement methods. If quantities of waste or chemical use decrease after a P2 effort is made, the decrease may be attributed to the P2 effort. However, other factors may also have influenced waste generation and chemical consumption. For instance, if the number of batches processed or quantity of product produced has decreased during that period, the change in waste may be related more to these external factors than to the P2 efforts made.

Production-adjusted measures of P2 account for changes in production activity as well as for changes resulting from P2 efforts. In other words, production-adjusted measures of P2 allow a firm to distinguish the components of waste change that are due to changes in production activity from those due to P2 measures implemented at the firm. Box ES-1 presents examples of production-adjusted P2 measures.

For production-adjusted P2 measures, a unit-of-product is the factor used to adjust gross quantities of waste or chemical use to infer the amount of pollution prevention progress by individual firms and groups of firms. If a firm has made no pollution prevention improvements, production-adjusted P2 measures should show no change in waste generation per unit-of-product. If pollution prevention changes have been implemented, adjusted figures should show a decrease in waste generation per unit-of-product. Box ES-2 shows one example of how a unit-of-product can be used to better assess P2 measurement data.

Box ES-1.

Typical Ways to Measure P2

Not Production-Adjusted

- **Change in quantity of emissions** "Reduced discharge of chromium by 20% last year"
- **Change in quantity of chemical or raw materials used** "Reduced plating solution purchases by 10% last year"

Production-Adjusted

- **Change in quantity of chemical used per unit product** "10% reduction in quantity of plating solution used per part shipped last year"
- **Change in quantity of chemical used per unit activity** "Reduced solvent use by 15% for every hour the degreaser ran last year"

Box ES-2.

Using Unit-of-Product to Calculate P2 Improvements Can Filter out Effects of Change in Production Activity

In 1993, Canton Circuits (a hypothetical firm) generated 22,000 pounds of trichlorethylene (TCE) waste from a vapor degreasing operation used to remove oil from the 16,000 metal circuit boxes it manufactured. In 1994, after making several pollution-prevention changes, Canton generated 15,000 pounds of trichloroethylene waste in cleaning 20,000 circuit boxes. Under SARA, Canton could measure P2 progress for the degreaser as follows:

$$\text{Unit-of-Product Ratio:}\ \frac{\text{Boxes in 1994}}{\text{Boxes in 1993}} = \frac{20{,}000}{16{,}000} = 1.25$$

Using the Unit-of-Product Ratio

The production ratio is used to calculate the expected waste generation, given this year's level of production, if no pollution prevention changes had been made during the past year. Expected waste generation in 1994 is calculated as follows:

(production ratio) · (1993 waste generation) = (1.25) · (22,000) = 27,500 lb

1994 actual waste generation - 15,000 lb, inferring 12,500 lb waste reduction. This measure of waste reduction filters out the effects of increased production at Canton.

Using Unit-of-Product to Assess P2 Changes on Efficiency

Another way to examine the effects of P2 is to assess whether the amount of waste per "widget" produced has changed. Using Canton Circuits' data, the calculations would be as follows:

(TCE waste generated in 1993)/(number widgets produced in 1993) = (22,000)/(16,000) = 1.38 lb TCE per circuit box produced

(TCE waste generated in 1994)/(number widgets produced in 1994) = (15,000)/(20,000) = 0.75 lb TCE per circuit box produced.

The two waste efficiencies would then be compared to conclude that Canton had made substantial waste reductions of 0.63 lb TCE per circuit box produced.

Often pollution prevention activities are aimed at reducing waste or emissions. However, P2 also includes the concept of *usage* of raw materials, particularly hazardous raw materials. Materials that are not introduced into a production process cannot leave that process as waste or emissions. Thus, reduction of materials usage is an important part of the universe of pollution prevention, and changes in materials usage can be a measure of P2.

ES.2 Project Objectives

Three objectives were addressed in researching production-adjusted measures of P2:

1. To describe different methods and systems that firms are using to measure pollution prevention;

2. To develop methodology for application of statistical and graphical analysis for evaluating production-adjusted measurements of P2; and

3. To apply the statistical and graphical methodology to "real world" data provided by case study sites.

ES.2.1 Existing P2 Measurement Systems

The report describes five facilities that are currently using production-adjusted measures of P2. These facilities were chosen to represent both small and large facilities, as well as those using complex and simple systems for P2 measurement. The case study firms include a metal finishing shop, two electronics firms, a pharmaceutical firm, and a paper recycling facility.

ES.2.2 Evaluating Production-Adjusted P2 Measures

Under this research, a methodology was developed which applies statistical and graphical tools to assess the accuracy of different units-of-product used in P2 measurement. The primary focus of the methodology is to find a unit-of-product that is closely related to the waste being targeted.

The following example shows the importance of finding a unit-of-product that is closely related to the waste or chemical usage being targeted. Imagine a production facility that has modified its degreasing equipment to reduce solvent loss. Suppose this facility finds that it has reduced its purchase of solvent by X gallons after the change is made, and that it has cleaned Y parts in the month before the change was made and Z parts in the month after the change was made. If the loss of solvent has more to do with the number of hours that the degreaser was running than with how many parts were cleaned, then "solvent savings per part cleaned" is a random number. "Solvent saved per hour of operation," however, would provide a good picture of the actual savings resulting from the change. A unit-of-product that is closely related to a target waste stream or chemical usage is said to be well-correlated with the waste or chemical usage in question (shown in Figures ES-1 and ES-2).

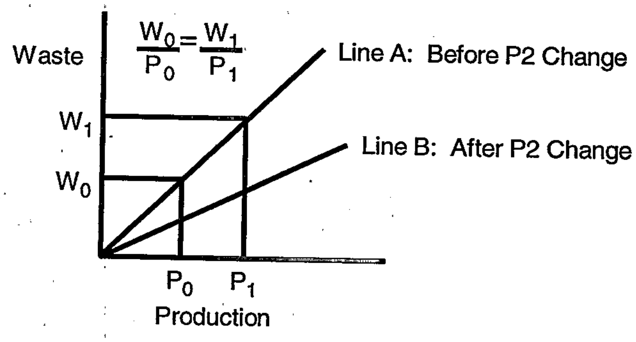

Figure ES-1. Well-correlated unit-of-product relationship between waste and a related unit-of-product before and after P2 improvements.

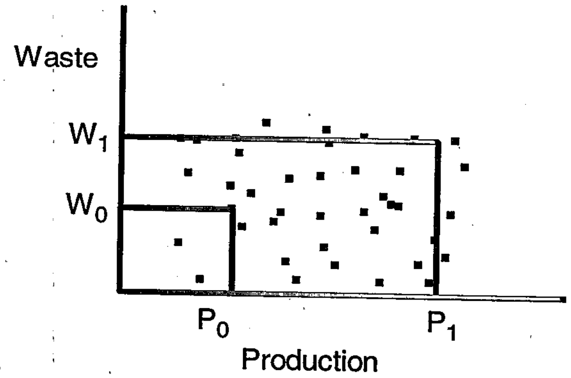

Figure ES-2. Plot of production and a waste that is not strongly correlated to production. No relationship can be detected.

The methodology for assessing the relationship between a unit of product and a given waste stream or chemical use stream is shown in Figure ES-3.

ES.2.3 Application of Methodology

The research team tested the methodology for applying statistical and graphical tools to assess units-of-product by applying it to data supplied by the five case study facilities. The case study facilities consisted of manufacturers in metal finishing, semiconductor fabrication, electronics, pharmaceuticals, and paper recycling. This process allowed the research team to assess the usability of the methodology in a practical setting.

Using real-world data also allowed the research team to make a preliminary assessment of how different units-of-product might correlate with key waste streams or key chemical inputs in other firms in the same industries.

ES.3 Results

Use of Production-Adjusted P2 Measurement

Although the major driver for developing production-adjusted measurements of P2 has been regulatory requirements, firms have also found these measures to be useful for other reasons.

The process of setting up a production-adjusted P2 measurement system can have benefits beyond those of fulfilling regulatory reporting needs; conversely, some systems that have been set up for other applications (e.g., statistical process control, product pricing) can be used to generate P2 measurement values.

In addition to providing a way to track pollution prevention progress, production-adjusted measures of P2 provide firms with a more detailed understanding of waste generation and chemical use patterns. This insight can help firms fine-tune their production processes to improve efficiency.

Measuring P2 can be a resource-intensive process. It is important to ensure that the resources expended are in line with the benefits accrued. It is counterproductive to spend many staff hours to develop and implement a measurement system if no resources will be left to actually implement P2 projects. Likewise, a P2 measurement system should be selected that is appropriate to the production process or facility being measured: if the process is constantly changing, the measurement system should

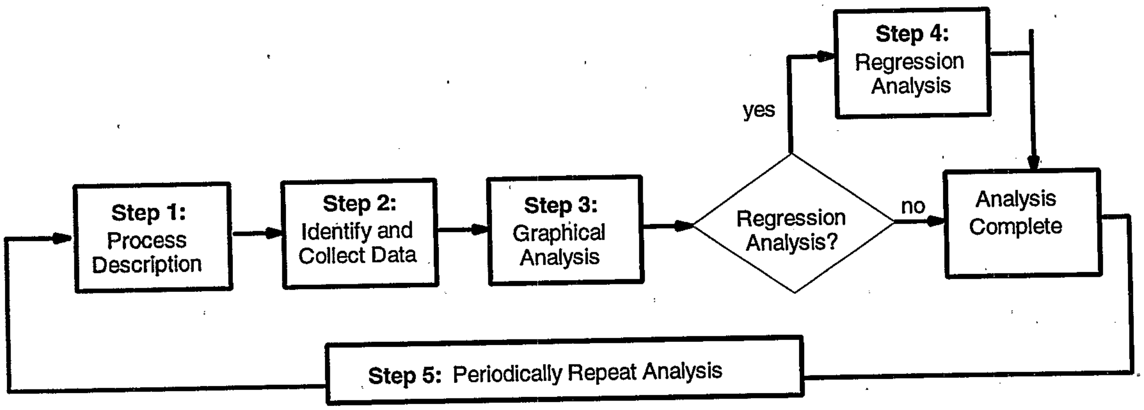

Figure ES-3. Five steps for unit-of-product analysis.

accommodate changes. If the product in question is being phased out, then a more rudimentary measurement may be in order.

Application of Project Methodology

Testing the project methodology with facility data showed that it was possible to use the methodology to assess production-adjusted measures of P2 at different manufacturing facilities.

Finding data to use in the methodology for verifying units-of-product for P2 measurement requires extensive and thorough communication among firm personnel, from production engineers to accounting staff. Careful attention must be paid to the sources and time frame of the data. For instance, it is important to know whether the production data supplied by a department refers to actual line production or to shipments from inventory.

It may be difficult to obtain enough waste generation data points to use this project's methodology to directly assess a measurement of P2 based on changes in waste generation. Depending on the particular production process, it may be possible to substitute chemical use data as a surrogate for chemical waste. Chemical use data can then be used to assess the waste-based P2 measure or can be used to construct a use-based P2 measure.

Assessing a unit-of-product used in a production-adjusted P2 measurement system is an iterative process. Users of the methodology presented in this report must understand the objectives of the analysis and periodically assess how well the methodology fits the available data.

Conclusions about Units-of-Product Used by Case Study Facilities

Use of the case study facilities allowed researchers to examine the workings of five different production-adjusted measures of P2 in five different industries. These units-of-product used by the case study facilities are summarized in Table ES-1.

The research team detected a statistically significant relationship between single units-of-product (e.g., "square feet plated" or "kilograms of product produced") and chemical usage at the case study facilities. In the case study facility for which waste data were analyzed, correlation was also found between waste and a single unit-of-product.

This finding is significant because there has been some concern that single units-of-product are inadequate to explain variation in waste generation. If this were true, then it would be much more difficult for firms to accurately assess their P2 performance, as they would have to account for many more variables than a single, measurable output. The results of this research, however, suggest that a carefully chosen single variable unit-of-product can account for enough of the variation in chemical use or waste to be used in adjusting gross P2 measures.

Table ES-1. How Well Units-of-Product Explained Variation in Chemical Use and Waste Generation

Industry	Unit-of-product used for adjusting pollution-prevention measurement	Did unit-of-product explain variations in: Chemical use for key inputs?	Did unit-of-product explain variations in: Waste generation for key waste streams?	Facility or company-wide measure or process specific?
Metal finishing	Square feet substrate plated or coated	Yes	NA[a]	Process-specific
Paper recycling	Tons of paper produced	Yes	NA	Facility-wide
Semiconductor fabrication	Combined unit-of-product incorporates number of memory chips, logic chips, and masks produced [as surrogate for technological content of product]; number of module parts produced	Combined unit-of-product correlated for some chemicals, not for others; module parts correlated for all chemicals[b]	Number of bits (a component of the combined unit-of-product) correlated with one waste stream; module parts correlated with same waste stream[b]	Facility-wide
Electronics production	Number of passes substrate makes through process	Yes	NA	Specific to each product line
Pharmaceutical production	Kilograms of product produced	Yes	Yes	Specific to individual department

[a] NA = Not applicable.
[b] Results somewhat uncertain; see Section 4.3.3 for full discussion.

Section 1
Introduction

Accurate and meaningful measurement systems are essential to the long-term success of Pollution Prevention (P2) in industrial settings. As companies move beyond short-payback P2 projects to longer-term, capital-intensive P2 activities, corporate management will rightly demand accounting of the environmental and cost benefits of these projects. In addition, many regulatory bodies and community groups are beginning to ask individual facilities to demonstrate that they are making progress in improving environmental performance. Credible methods of measuring P2 will be key elements in any of these requirements. The U.S. Environmental Protection Agency's (EPA's) Office of Research and Development (ORD), Research Triangle Institute (RTI), and Greiner Environmental undertook research to understand the methods and structures that firms are using to measure pollution prevention.

In particular, the objective of this research was to investigate P2 measurement that reflects changes in emissions, waste, or chemical usage, and also reflects variations in production levels. This kind of P2 measurement is referred to in this report as "production-adjusted P2 measurement." Other authors refer to it as "normalized" or "indexed" measurement of P2 (Harriman et al., 1991).

1.1 Background of P2 Measurement in General

P2 measurement issues come up along a spectrum of applications:

- ➡ Measuring effects of a single P2 project on one process line
- ➡ Measuring P2 for a single facility or company
- ➡ Measuring national, state, or industry sector P2 progress.

This research looks in detail at P2 measures for a specific facility or production line. Others have addressed the issues of measuring P2 on larger scales. See, e.g., Tellus et al., 1991.

1.1.1 Who Uses P2 Measurement and Why

The users of P2 measurement are identified in Box 1-1. It became clear as this research progressed that there is broad interest in P2 measurement. It ties into many different areas of environmental policy and regulation in this country.

P2 as Measured by Change in Materials Usage. Often pollution prevention activities are aimed at reducing waste or emissions. However, P2 also includes the concept of *usage* of raw materials, particularly hazardous raw materials. Hazardous materials that are not entered into a production process cannot leave that process as waste or emissions. Thus, reduction of hazardous materials use is included in the universe of pollution prevention.

In this research data regarding changes in quantity of raw materials were often used as a way of assessing P2 progress. In this report, we use the term "chemical usage" rather than "raw

Box 1-1.

Who Can Use This Report?

Facility staff in industries examined in these case studies. Areas of interest to them include:

- The effectiveness of the production-adjusting units used by the facilities we visited.
- The aspects of measurement systems that were successful and those that were not as useful.
- How the measurement system added value to the process or improved quality of product.
- What types of data are used by other facilities to measure P2.

People in other industrial sectors who are considering whether and how to measure P2. Topics of interest to this audience include:

- The characteristics of the P2 measurement systems that seem to be effective.
- What types of data are used by other facilities to measure P2.
- Information about how P2 measurement has been valuable to companies.

EPA ORD staff. Topics of interest include:

- Sources of good data at facilities (likely to be of particular interest to people who are working on P2-related software).
- Information about factors that have led to successful P2 measures at facilities.

Regulatory policy staff. Topics of particular interest will be:

- Information about the potential accuracy of relationship between P2 measurements that a facility generates and the kind of P2 that is actually occurring.
- Information about what kinds of P2 data can be generated at facilities and possible overlaps with toxic release inventory (TRI) information.
- Information about uses for chemical use data in measuring P2.

Citizens Groups/Environmentalists, particularly those who want to find national tools to measure P2. Information of particular relevance includes:

- General description of the issues involved in developing an accurate measure of P2 at a facility.
- Information about the limitations of various approaches to P2 measurement as applied to specific facilities.

material usage." This is because the raw materials in question were chemicals subject to environmental regulation. Despite this use of terminology, there is no reason that the methodology employed here could not be used to assess measures of non-hazardous waste generation and nonchemical materials use.

1.1.2 Production-Adjusted Measures of P2: A More Detailed Look

If quantities of waste or chemical use decrease after a P2 effort is made, the decrease may be attributed to the P2 effort. However, other factors may have also influenced waste generation and chemical consumption. For instance, if the number of batches processed or quantity of product produced has decreased during that period, waste reduction may be more properly attributed to these external factors than to the P2 efforts made. Production-adjusted measures of P2 account for changes in production activity as well as accounting for changes resulting from P2 efforts. Another way of stating the same concept is that production-adjusted measures of P2 allow a firm to separate out the components of waste change that are due to changes in production activity vs. those due to P2 measures implemented at the firm. Box 1-2 presents examples of production-adjusted P2 measures. In addition, companies that report under the Federal Superfund Amendments and Reauthorization Act (SARA) Title III Section 313 (Toxics Release Inventory) and under the reporting acts of several states (e.g., Massachusetts and New Jersey) are required to report a production-adjustment factor along with information about releases or chemical use.

The Unit-of-Product. For production-adjusted P2 measures, a unit-of-product is the factor used for adjusting gross quantities of waste or chemical use to infer the amount of pollution-prevention progress by individual firms and groups of firms. If a firm has made no pollution-prevention improvements, production-adjusted P2 measures should show no change in waste generation per unit-of-product. If pollution prevention changes have been implemented, adjusted figures should show a decrease in waste generation per unit-of-product. Box 1-3 shows one example of how a unit-of-product can be used to better assess P2 measurement data.

Box 1-2.

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Businesses use production-adjusted P2 measures for many reasons other than reporting requirements. Many businesses find production-adjusted data useful for:

- Gaining insight into chemical use and process efficiency;
- Setting P2 goals and measuring progress against those goals;
- Comparing corporate process, facility, and division performance; and
- Communicating P2 progress to stakeholders.

Production-adjusted P2 Measurement Issues Addressed in This Report. This research investigated three topics related to production-adjusted P2 measurement:

1. **Case studies providing a snapshot of firms that use production-adjusted P2 measurement**: How firms currently use measures of P2. How they select the measurement method they use. How valuable it is to the firm to have a production-adjusted measure of P2.

2. **Develop methodology to apply graphical and statistical tools for assessing the accuracy of different production-adjusted measures of P2.**

3. **Preliminary assessment of the accuracy of how the case study facilities production-adjusted their P2 measures.**

In addressing the first topic, we identified five facilities that are currently using production-

Box 1-3.

Using Unit-of-Product to Calculate P2 Improvements Can Filter out Effects of Change in Production Activity

In 1993, Canton Circuits (a hypothetical firm) generated 22,000 pounds of trichlorethylene (TCE) waste from a vapor degreasing operation used to remove oil from the 16,000 metal circuit boxes it manufactured. In 1994, after making several pollution-prevention changes, Canton generated 15,000 pounds of trichloroethylene waste in cleaning 20,000 circuit boxes. Under SARA, Canton could measure P2 progress for the degreaser as follows:

$$\text{Unit-of-Product Ratio: } \frac{\text{Boxes in 1994}}{\text{Boxes in 1993}} = \frac{20{,}000}{16{,}000} = 1.25$$

Using the Unit-of-Product Ratio

The production ratio is used to calculate the expected waste generation, given this year's level of production, if no pollution prevention changes had been made during the past year. Expected waste generation in 1994 is calculated as follows:

(production ratio) • (1993 waste generation) = (1.25) • (22,000) = 27,500 lb

1994 actual waste generation - 15,000 lb, inferring 12,500 lb waste reduction. This measure of waste reduction filters out the effects of increased production at Canton.

Using Unit-of-Product to Assess P2 Changes on Efficiency

Another way to examine the effects of P2 is to assess whether the amount of waste per "widget" produced has changed. Using Canton Circuits' data, the calculations would be as follows:

(TCE waste generated in 1993)/(number widgets produced in 1993) = (22,000)/(16,000) = 1.38 lb TCE per circuit box produced

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The two waste efficiencies would then be compared to conclude that Canton had made substantial waste reductions of 0.63 lb TCE per circuit box produced.

adjusted measures of P2 and worked with them to document their methods and results. This information is presented in Section 3 of this report. To address the second topic, we developed a methodology for applying statistical and graphical tools to evaluate different units-of-product used in production-adjusted P2 measurement. This is presented in Section 2. We applied this method to data that the case study facilities shared with us. This allowed us to test the usability of the methodology, as well as to provide initial indications about the usefulness of various potential production-adjusting "units-of-product" for the industry sectors represented by the case study facilities. These results are presented in Section 4. Section 5 provides conclusions from this work. Appendixes A and B give relevant references.

In addition, we developed a framework for selection and use of production-adjusted measures of P2. The framework is based on the information shared by the case study facilities and the information obtained through the analyses conducted during this research. The framework is presented as Appendix C of this report.

Section 2
Description of a Methodology for Application of Statistical and Graphical Tools to Assess Accuracy of P2 Production-Adjusting Units

A key component of the P2 measurement framework is evaluation of the unit-of-product used to adjust the P2 measurement to account for variation in production. To create an accurate measure of the effects of a P2 effort, it is necessary to find a unit-of-product that is closely related to the waste being targeted. To illustrate, imagine a production facility that has modified its degreasing equipment to reduce solvent loss and finds that it has reduced its purchase of solvent by X gallons after the change is made. Suppose further that they have cleaned Y parts in the month before the change was made and Z parts in the month after the change was made. If the loss of solvent had more to do with the number of hours that the degreaser was running, rather than how many parts were run through it, then the "solvent savings per part cleaned" is a random number, whereas "solvent saved per hour of operation" would provide a good picture of the actual savings resulting from the change. This would provide a comparison with which to measure later P2 changes.

2.1 Evaluating a Unit-of-Product

Companies that file under the Federal Toxics Release Inventory (TRI) are required to report a unit by which their reported levels of emissions and releases can be adjusted. This is known as the "production ratio" or "activity ratio" or the "unit-of-product." The purpose of a production ratio or an activity index is to allow year-to-year comparisons of waste generation that are adjusted for the level of production. In addition, many companies want to track their P2 progress more accurately, assess their P2 investments, and communicate their achievements to stakeholders. Production-adjusted measurement helps accomplish these goals.

This section reviews a methodology for using statistical and graphical tools for assessing a unit-of-product. The methodology was developed for this project. It begins with an introduction to the unit-of-product concept. Data collection methods and requirements are then presented. Next, the section presents three graphical analysis tools and an overview of a regression analysis tool used to evaluate how well a unit-of-product explains the variation in key pollution or chemical use figures.

2.1.1 The Unit-of-Product

A unit-of-product is used to adjust the overall measure of changes in chemical use or waste generation. If a firm has made no pollution-prevention improvements, adjusted P2 measures should show no change in waste generation per unit-of-product. If successful pollution-prevention changes have been implemented, adjusted figures should show a decrease in waste generation per unit-of-product.

2.1.2 Choosing a Unit-of-Product

The goal to keep in mind when choosing a unit-of-product is to select one that is well correlated to chemical use or waste generation. This means that waste per unit-of-product is constant whatever the level of production, e.g., when production increases, generation increases proportionally and waste per unit-of-product remains constant. Line A in Figure 2-1 depicts this linear relationship between waste and production data. Mathematically, the slope of the line (W/P) is constant. Under this assumption, if a P2 change were implemented, the change would lead to a new relationship between production and chemical data—represented as Line B in Figure 2-1.

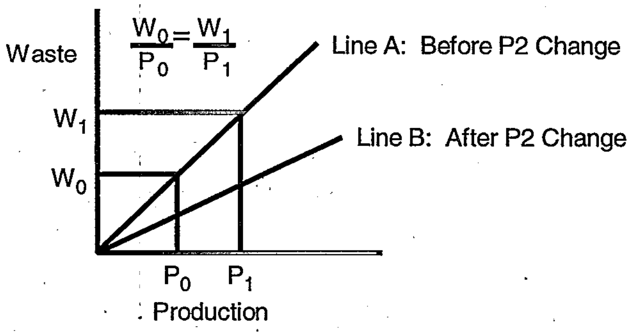

Figure 2-1. Well-correlated unit-of-product relationship between waste and a related unit-of-product before and after P2 improvements.

A poorly correlated unit-of-product will not measure P2 progress adequately. For example, when production doubles, waste generation does not increase proportionally. This means waste per unit-of-product is not constant but depends on the level of production. As a result, a poor unit-of-product will under- or over-estimate P2 progress. Figure 2-2 represents a poorly correlated unit-of-product where there is a random relationship between waste and production. The waste per unit-of-product ratio (W/P) is different for most points. There is no consistent, predictable relationship between waste and the unit-of-product. Thus, variations in the W/P ratio cannot be said to be attributable to P2 efforts.

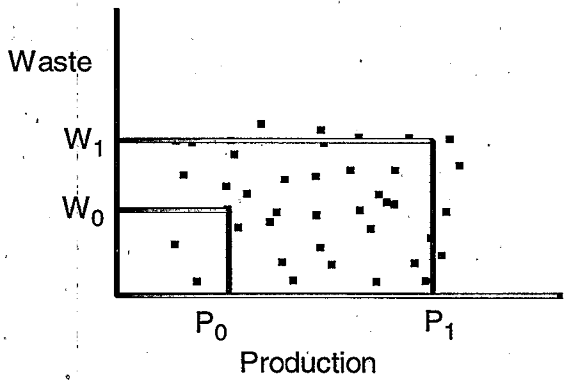

Figure 2-2. Plot of production and a waste that is not strongly correlated to production. No relationship can be detected.

Identifying a well-correlated unit-of-product will be easiest in cases where:

- There are few uses of a chemical at the site. The greater the number of uses, such as the case where a cleaning solvent is used in six different sites around the plant, the more difficult it is to find a measure of production that correlates with the waste stream containing this chemical.
- There is little variation in the products produced using the chemical. Variation in product types (such as printed circuit boards and subassemblies) and attributes (such as

surface area, geometric shape, or substrate type) makes finding a unit-of-product more complex since each attribute can affect waste generation differently.

- There is little change in processes. Processes that are constantly changing make measurement from year to year more difficult. Firms with less variable production find it easier to find a unit-of-product since processes and products remain relatively constant from year to year.

Choosing a well-correlated unit-of-product is further confounded by one important constraint—are the data available? Firms can only choose among potential units-of-product for those that the company has historical data or is willing to collect new data. This is an obvious but very real constraint since many candidates are not tracked on a regular basis.

2.2 Analyzing the Unit-of-Product

How can an environmental professional choose a unit-of-product that is well correlated to a given chemical's use or waste generation? Two analytical methods are presented here—graphical analysis and regression analysis. Graphical analysis is used to qualitatively assess a unit-of-product. Graphical analysis methods include preparing histograms, time-series plots, and scatter plots. Graphical analysis is also a preliminary step when performing regression analysis. See Figure 2-3.

Regression analysis is used to evaluate a unit-of-product quantitatively. Regression analysis involves calculations to determine the degree of correlation between chemical and production data. Whether graphical methods alone are used or graphical and regression methods are used together, a multistep data collection and analysis process should be followed when evaluating a unit-of-product.

Step 1. Process Description

The purpose of this step is to map out the process under investigation. This step involves drawing a flow diagram, tracing the chemical's path through the process, and noting chemical inputs, outputs, and conversions. The level of complexity of the flow diagram will vary depending on the level of accuracy one needs for the analysis.

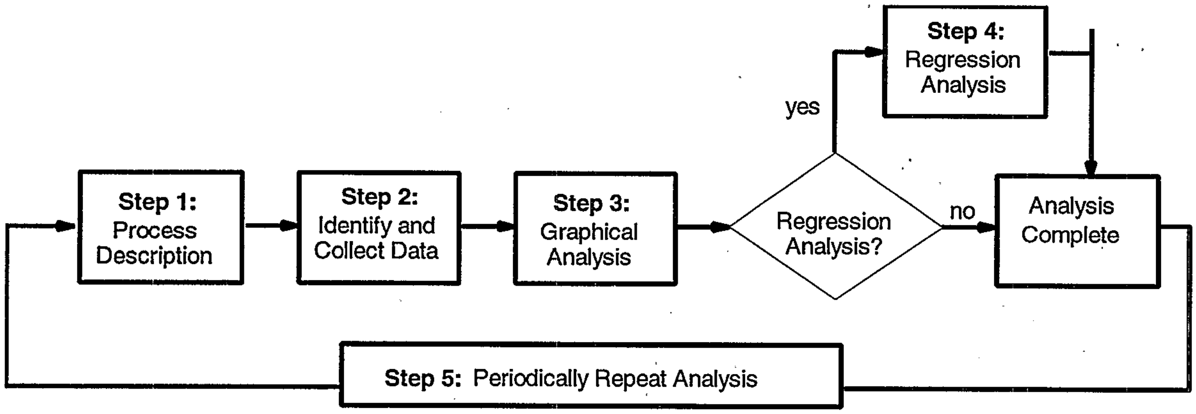

Figure 2-3. Five steps for unit-of-product analysis.

Step 2. Identify and Collect Time Consistent Data

To analyze a unit-of-product, it is necessary to have time-consistent chemical and production data. The term "time consistent" means that the chemical data and production data must correspond to the same time period, e.g., daily pounds of xylene used and daily square feet painted. Analysis cannot be performed on data from different times, e.g., daily square feet painted and weekly pounds of xylene used.

Chemical data can be found in process engineering records, materials accounting records, or process control charts. Production data are typically found in production logs. The data set should cover an adequate number of time periods to allow trends and relationships to be apparent. We recommend attempting to have at least 30 time periods (e.g., 30 days or 30 weeks) in the analysis data set. More time periods are preferable because more data points improve the accuracy of the analysis.

Analysis will be improved where there is some variation in production levels during the time periods being investigated. This is because data trends are easier to see when the data are not entirely clustered around one set of values.

If regression analyses are to be used to analyze the data, the data should be collected over a time period during which there were no major changes to the production process. For a regression analysis to be meaningful, it requires data from a process that has performed consistently. This consistency requirement makes the use of quarterly or monthly data undesirable in regression analysis since it is likely that some major change to the process would have occurred over a 30-month or 30-quarter time period.

More often than not, firms find that they can use chemical use data (as opposed to waste data) to evaluate their unit(s)-of-product. Chemical use data can be monitored on a real-time basis—but waste volumes are difficult to monitor in this way. Waste data are typically calculated once a year for reporting purposes. Waste data are also often estimated from material balance calculations rather than measured directly. For example, while it is difficult to measure weekly waste generation (emissions) from a solvent degreaser, directly measuring solvent use is relatively straightforward. Further, using waste inventory data for the purposes of unit-of-product analysis can be problematic. This is because waste inventory data often lag behind actual waste generation, and data about offsite shipments often reflect more information about the waste hauler's schedule than about waste generation rates.

Step 3. Graphical Analysis

Graphical analysis allows one to see data patterns and is a relatively simple way to look at the fit between measures of production and chemical data. Specifically, plots of production and chemical data allow one to see:

- Distribution of the data (i.e., normal, bimodal, etc.) and trends in the data;
- Extreme data points or outliers (e.g., very high or very low values); and
- Data entry errors (errors are easiest to spot when they have extreme values).

Graphical analysis tools include histogram plots, scatter plots, and time-series plots. These tools are reviewed in detail in Section 2.2.1.

Step 4. Regression Analysis

After completing a graphical analysis, firms can choose to review the data further by performing a regression analysis. Whereas graphical analyses provide a qualitative sense of the correlation between production and chemical data, regression analyses provide a quantitative measure of the correlation between production and chemical data. Whether a firm chooses to perform a regression analysis depends on whether the firm:

- Has the resources (expertise and software) to analyze the data,
- Wants a quantitative measure of whether its unit(s)-of-product are well correlated, and
- Finds the qualitative graphical analysis results inconclusive.

If the company performs regression analysis, it must determine whether to use simple linear regression or multiple regression methods. Simple linear regression can be performed with most hand-held calculators or spreadsheet software programs. Simple linear regression is appropriate when examining the correlation of a single unit-of-product (e.g., square feet plated). Multiple regression is used when examining whether some unit-of-product combination (e.g., square feet plated, amp hours, and number of parts) correlates with chemical data. In general, multiple regression analysis is much more complex than simple linear regression. Regression analysis is discussed in Section 2.2.2.

Step 5. Repetition

Once the analysis is complete, it should be repeated periodically (especially after major changes to the process) to make sure the chemical and production data are still correlated. Figure 2-3 depicts this multistep method for analyzing a unit-of-product.

2.2.1 Graphical Analysis

This section reviews three graphical analysis plots—histogram plots, scatter plots, and time-series plots. When evaluating a unit-of-product, one should prepare and examine each of these plots.

Histograms. Histograms provide a picture of the frequency distribution of a data set. The frequency is shown by drawing a rectangle whose base is the "chemical data per unit-of-product interval" (i.e., quantity sulfuric acid/ pound of paper) on the horizontal axis and whose height is the corresponding frequency. In this report, the x-axis of histograms is marked in "bins." A bin is a range of values (i.e., values falling between 10 and 15, 16 and 20, and so on). The height of the bar shows how often values from a given data set fall within that range of values. Bell-shaped histograms are indicative of a process undergoing normal variation. Furthermore, bell-shaped histograms are also indicative of a well-correlated unit-of-product. If the histogram does not have a bell shape, the ratio of chemical data to production may be a poor choice. A histogram of the hypothetical paper manufacturing data is shown in Figure 2-4. Notice the normal distribution of the data. While the plot indicates that tons of paper produced is a good unit-of-product for sulfuric acid, one should prepare scatter and time-series plots before drawing conclusions.

Histograms also help the investigator to see whether one or several "extreme" data points are affecting the overall mean. Extreme data points could also indicate particularly wasteful or particularly efficient periods of operation that warrant further examination. For example, the

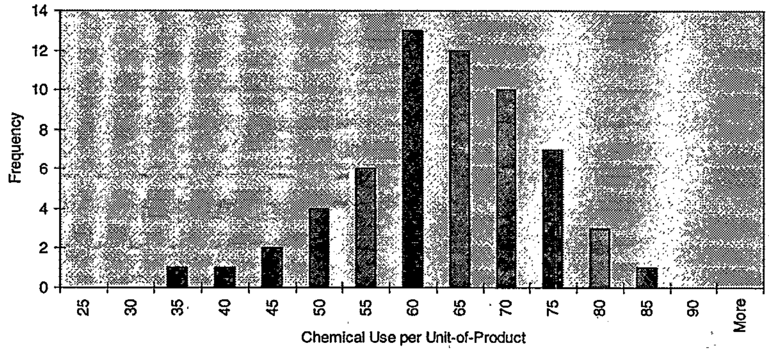

Figure 2-4. Sulfuric acid use per ton of paper histogram.

points representing the smallest values of chemical use per unit-of-product are valuable from a P2 perspective. The firm's engineers could use them to identify optimal operating conditions. If the paper manufacturer replicated these operating conditions, the company would significantly reduce sulfuric acid use, waste, and raw material cost.

Scatter Plots. Scatter plots are used to examine the relationship between chemical and production data. If the two are perfectly correlated, the points in a scatter plot would line up evenly and one could draw a straight line through each point (Figure 2-1). If chemical and production data are not correlated, the scatter plot would have no discernible pattern—just a random scatter of data points through which no line could be drawn (Figure 2-2). Most scatter plot data fall somewhere between these two extremes. After preparing a scatter plot, it is good practice to draw a "best fit" line through the data. The easier it is to draw such a line, the stronger the correlation between chemical and production data. The slope of this line represents the average chemical use per unit-of-output.

The scatter plot in Figure 2-5 depicts the hypothetical paper manufacturing data set. The plot shows an increasing relationship between production and chemical use—indicating that the two are correlated. Taken together, the scatter and histogram plots strongly suggest tons of paper produced would be a good unit-of-product to measure sulfuric acid P2 progress.

Time-Series Plots. Time-series plots are useful for data that have been collected sequentially. When one plots the observations in time sequence, trends and cycles often become apparent. Data that either consistently increase or decrease should be viewed with caution. Consistently increasing or decreasing trends indicate that the process is unstable and is not undergoing normal day-to-day variation. Good normalization data should have a random time-series plot. The time-sequence plot of the paper manufacturing data set shows a random trend (Figure 2-6).

Taking the paper manufacturing histogram, scatter, and time-series plots together, it appears that sulfuric acid use and tons of paper produced are correlated—high levels of sulfuric acid use correspond to high levels of production. This conclusion is derived from the fact that

- The histogram of sulfuric acid use per unit-of-output is bell-shaped;
- The scatter plot shows an increasing trend—a line depicting this trend can be drawn through the data; and
- The time series plot shows a random pattern as opposed to a constantly increasing or decreasing pattern.

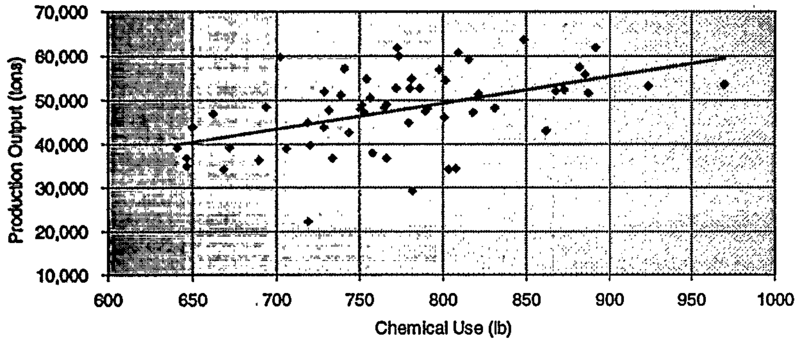

Figure 2-5. Scatter plot showing paper produced per pound of sulfuric acid.

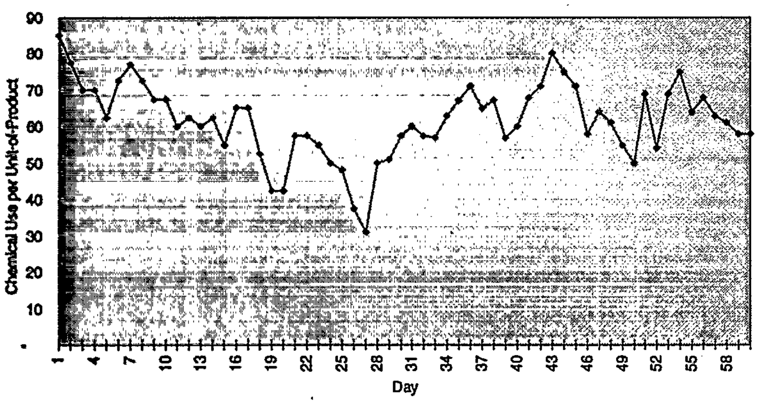

Figure 2-6. Time series plot showing sulfuric acid use per ton of paper.

The histogram and time-series plots also show 2 days where chemical use per unit-of-product was abnormally low. These days should be evaluated more closely since they represent periods of greater chemical use efficiency. If operating conditions on these 2 days could be replicated, the company would significantly reduce its waste generation and raw material cost.

Descriptive Statistics. After viewing the data graphically, it may become clear that there is an outlier in the data, i.e., a data value that is much larger or smaller than the rest of the data points. Compiling a set of descriptive statistics for the full data set and for the data set without the outlier can help the user understand the impact of the outlier on the data set. Descriptive statistics include values like the mean, standard error, median, mode, standard deviation, and confidence level. If the outlier is discovered to have a large impact on the data set, then the user may choose to exclude that data point for purposes of the unit-of-product analysis. Descriptive statistics are an analysis option available in many spreadsheet programs.

The confidence level descriptive statistic deserves particular explanation here. The 95% confidence level statistic shows the range around the calculated mean in which the true mean is likely to lie. Thus, if the descriptive statistics show that the mean for the data set is 25 units, and the 95% confidence level is 5.4 units, then we can be 95% sure that the true mean will lie within 5.4 units of the mean for the data set. That is, we can be 95% confident that the true mean is somewhere between 19.6 and 30.4.

2.2.2 Statistical Analysis

Unlike graphical analysis, regression methods calculate the correlation between chemical data and a unit-of-product. Regression tests can be particularly helpful when choosing between two possible units-of-product or when it is important to know the degree of correlation between chemical and production data. While regression methods quantitatively determine a unit-of-product's correlation, regression analysis requires expertise and either computer software or a hand calculator with statistical functions to analyze the data.

Before performing a regression, it is important to check use or waste per unit-of-product data to see if the data are normally distributed. The best way to see if a data set is normal or not is to examine the histograms generated in Step 3. The histogram should approximate a normal or "bell-shaped" distribution (see Figure 2-7). If the histogram is bi-modal (two humps, shown in Figure 2-8), skewed (most values high or low, shown in Figure 2-9), uniform (same frequency for all bins, Figure 2-10), or in some other way obviously non-normal a regression analysis should not be performed.

In cases where the data do not appear to be normal, the data can be mathematically "transformed" to a normal shape. Data are transformed by multiplying each data point by a factor such as log x, ln x, e^x, $1/x$, x^2, etc. The choice of a specific factor depends on the shape of the distribution (i.e., for skewed distributions, one would try a logarithmic transformation). There are good reference materials

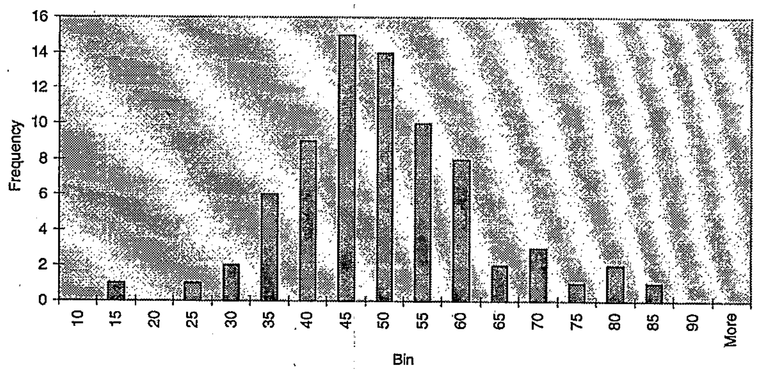

Figure 2-7. Histogram showing normal distribution of chemical use per unit-of-product data.

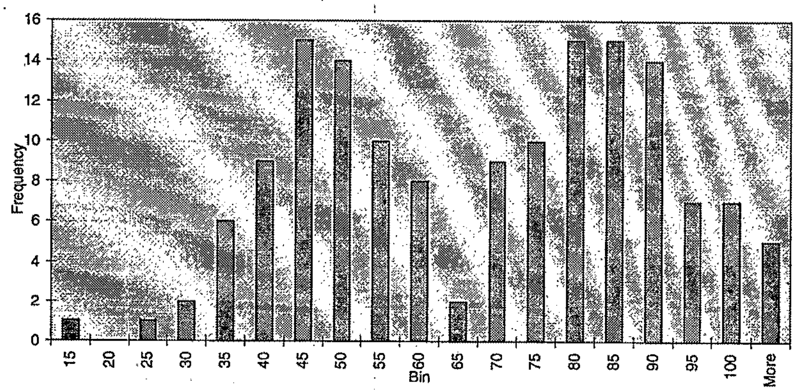

Figure 2-8. Histogram showing bimodal distribution of chemical use per unit-of-product data.

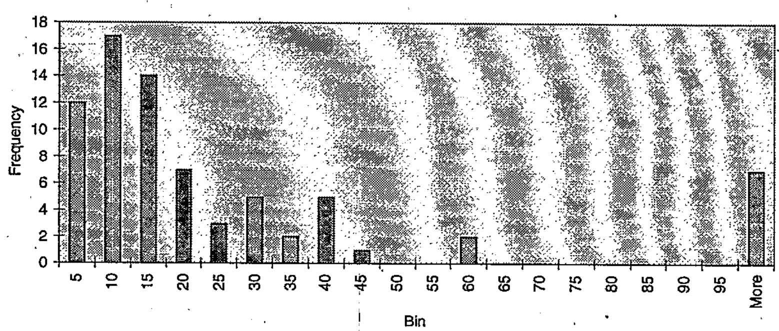

Figure 2-9. Histogram showing skewed (exponential) distribution of chemical use per unit-of-product data.

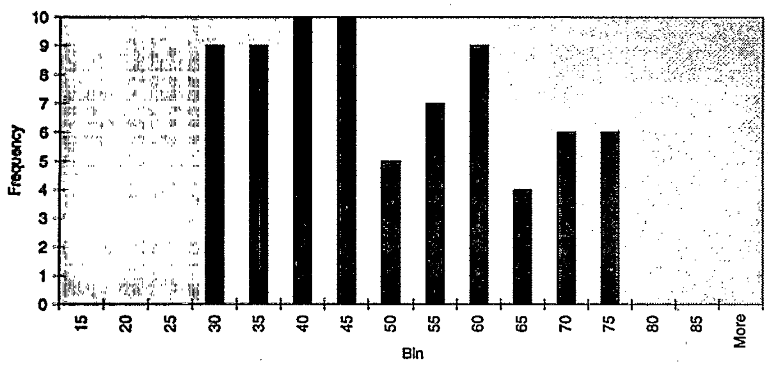

Figure 2-10. Histogram showing uniform distribution of chemical use per unit-of-product data.

available that provide guidance on how to transform data to make it more normally distributed (see Appendix B). Once one has reasonably normal data, it is time to proceed with regression testing.

Regression analysis can be divided into two related tests—simple linear regression and multiple linear regression. Which test one uses depends on the questions one wants to answer and the data one has in hand:

- Linear regression is used to look at the correlation between chemical data and a single unit-of-product (e.g., whether sulfuric acid use and pounds of paper manufactured are correlated).
- Multiple regression is used to look at the correlation between chemical data and more than one unit-of-product (i.e., whether xylene use and some combination of square feet painted, part depth, and number of parts per rack are correlated).

Simple Linear Regression. Mathematically, the simple linear regression model is defined as:

$$y = B0 + B1\ X + \text{error}$$

where:

B0	=	y intercept
X	=	slope
y	=	chemical data
X	=	production data
error	=	the error or deviation of the actual y value from the line B0 + B1 X.

In a regression analysis, production data are the independent variable (x) and chemical data are the dependent variable (y). Simple linear regressions can be run on spreadsheet programs such as Excel or on a statistical software package. The general procedure followed when using computer packages is for the user to input the data (x and y values) together with some instructions concerning the types of analyses that are required. The software package performs the analysis and prints the results in an output report. Output data that are useful for analyzing normalization data include: (1) B0 and B1 values, (2) the coefficient of determination (R-squared), and (3) a P-value.

B0 and B1 Values. Regression software packages generate an equation for a line that best fits the data. Usually expressed as coefficients, the regression produces intercept (B0) and slope (B1) estimates.

R-Squared. While the output of different software packages varies, all software regression analyses calculate a value known as the "R-squared" (r^2) term or "coefficient of determination." The R-squared term is a measure of the goodness-of-fit of the estimated regression line. It ranges from 0.0 to 1.0. For P2 measurement applications, R-squared values close to one are indicative of a good unit-of-product. However the R-squared term alone does not tell whether the relationship is statistically significant—for this the regression "P-values" must be known.

The R-squared term is a measure of the goodness-of-fit of the estimated regression line. It ranges from 0.0 to 1.0. In P2 applications, the R-squared value estimates how much of the variation in waste is explained by variation in the chosen unit-of-product. The closer an R-squared value comes to 1.0, the more of the variation in waste is explained by variation in that unit of product. However, the R-squared term alone does not tell the user whether he/she can be confident (in a statistical sense) that this relationship between waste and unit-of-product exists. In order to find out whether the relationship is statistically significant, the regression P-values must be calculated.

P-values. P-values indicate whether the values computed for B0 and B1 are statistically significant. A P-value of .05 for B1 indicates that we can be 95% confident that the relationship between our x and y variables is not random. The general rule for using P-values is as follows:

- P-values <0.05 indicate statistical significance
- P-values >0.05 indicate statistical insignificance.

Table 2-1 depicts a typical simple linear regression output. In this case, the regression was run on the paper manufacturing data using the spreadsheet program Excel.

Using Table 2-1, the equation for the line for the paper manufacturing data is:

$$\begin{aligned} y &= 1982 + 59X \\ \text{intercept} &= 1982 \\ \text{slope} &= 59. \end{aligned}$$

The slope gives the average chemical used per unit-of-product produced (59 lb chemical/lb of product). The R-squared value is .23—a low number for such an analysis (values near one are indicative of a good unit-of-product). The P-value for B1 is .0001 indicating 99.99% confidence that chemical use and production are correlated. The scatter plot, the line, the equation for the line, and the R-squared value are presented in Figure 2-11.

Table 2-1. Simple Linear Regression Output

Regression statistics		
R-squared	0.2294	
Observations	60.0	
Coefficients	**Coefficient value**	**P-value**
B0	1982	0.85794
B1	59	0.00010

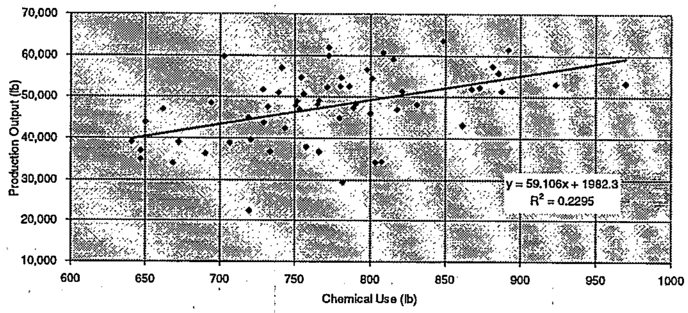

Figure 2-11. Scatter plot showing relationship between tons of paper produced and pounds of sulfuric acid used.

The regression results indicate that the average sulfuric acid use (in pounds) per pound of paper manufactured is equal to 59. This value is "statistically significant" because the P-value is <0.05. The R-squared term is equal to 0.23. This means that pounds of paper manufactured and sulfuric acid use are correlated. The quantity of paper produced explains 23% of the variation in sulfuric acid use. Obviously there are other factors—perhaps variation in raw material quality, ambient temperature, or operator factors—that are contributing to the remaining variation between the observed data and the regression line. The following conclusions can be drawn from regression analysis of the paper manufacturing data:

- Sulfuric acid use and tons of paper produced are correlated with a high degree of confidence (P value = .0001—therefore, one can be 99.999% confident the two are correlated);
- Since the correlation is strong, tons of paper produced is a good unit-of-product for sulfuric acid; and
- The amount of sulfuric acid used each day is affected by factors other than the amount of paper produced (since r^2 = 0.23).

Analysis of Residuals. The analysis of residuals plays an important role in validating the regression assumptions and results. For each observation in a regression analysis, there is a residual; it is the difference between the observed value of the dependent variable (y) and the value predicted by the regression equation. Most computer software programs will calculate and plot regression residuals.

The residuals in a residual plot should exhibit a random pattern. For example, the residual plot shown in Figure 2-12 has a random pattern. If the residuals are clustered or display spreading or narrowing patterns, the investigator should reexamine his/her data set and modify the regression model. The recommended way to modify the regression is to transform the data—a procedure outlined in Section 2.2.2 and described in greater detail in most regression text books.

Multiple Regression Analysis. Multiple regression analysis is used when one wants to determine whether two or more measure(s) of production are correlated with chemical data.

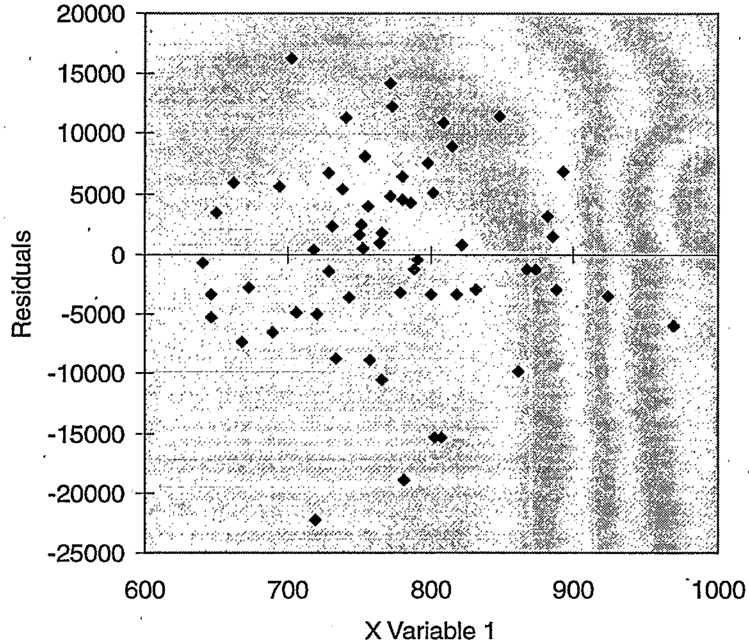

Figure 2-12. Residual plot showing random distribution of X variable residuals.

For example, in an electroplating process, do pounds of cyanide waste correlate to square feet plated, pounds of parts plated, number of parts plated, or some combination of these three measures of production?

In our sample data set we found that variations in paper production explained only 23% of the variation in sulfuric acid use. If understanding where such variation comes from is important, we could add other factors to our analysis—such as variation in raw material quality, ambient temperature, and line speed—by running a multiple regression. Mathematically, the multiple regression model can be expressed as:

$$y = B0 + B1\ X1 + B2\ X2 + B3\ X3 \ldots + Bn\ Xn + \text{error}$$

where:

- B0 = y intercept of the line
- Bn = the coefficient for Xn
- y = chemical data
- X = production data
- n = the nth measure of production in the model
- error = the error or deviation of the actual y value from the line B0 + B1 X.

Multiple linear regressions are most often run on statistical software packages such as Systat. Running and interpreting multiple linear regression data requires more sophisticated understanding of regression techniques. Practitioners should refer to regression analysis textbooks and guides when conducting such analyses. See Appendix B for references to text.

Section 3
Five Examples of Systems That Use Production-Adjusted P2 Measurement

Our research sought to investigate how production-adjusted measures of P2 were being used at the facility and process level in industry. We identified five industrial facilities and analyzed the production-adjusted P2 measurement methods that they use. Our objective was to select case study facilities that represented larger and small industry, as well as representing different complexities of process. Given those objectives, we identified a set of candidate firms and invited them to participate in the case studies. Prerequisites for participation also included willingness to share data and host day-long site visits.

The purpose of this section is to describe the P2 measurement methods used at the case study facilities. In particular, this section focuses on:

- Measure of production-adjusted P2 used,
- Data required for the measurement method, and
- Function the measurement method serves at the facility or corporate level.

Table 3-1 summarizes the P2 measurement systems at the case study facilities.

3.1 Greene Manufacturing, Connorsville, Indiana

Greene Manufacturing Company is a metal finishing job shop in Connorsville, Indiana. Greene employs roughly 130 persons. Its parent company is headquartered in Racine, Wisconsin. The Connersville Division is a direct supplier to Ford and an indirect supplier to GM and Chrysler. The company plates automobile and light truck tubes, heaters, and other automotive and nonautomotive parts.

Greene's pollution-prevention measurement system is an offshoot of the company's quality tracking system. Greene Manufacturing tracks its manufacturing operations by measuring the square footage of every part it plates. Data are recorded on log sheets and tallied daily, weekly, monthly, and yearly. Greene uses these data to price its products and control its plating baths. The data are also used to track pollution-prevention projects.

3.1.1 Description of Facility P2 Measurement System

Greene measures P2 by tracking daily chemical use, hazardous waste, daily off-spec parts and daily production in logbooks. The charts are then entered into spreadsheets by an administrative staff person. That same person then prints out charts showing the following metrics:

- Weekly change in plating sludge and hazardous waste per square foot plated, and

> "If we measure it, then we can fix it."
> — Brad Crowe, Greene Mfg.

Table 3-1. Summary of Information about Five Case Study Sites

Positive Attributes	Negative Attributes
Green Manufacturing—P2 measurement calculated by staff using data from logs.	
Positive Attributes ■ Weekly calculation and communication provide incentive for greater worker efficiency ■ Used to communicate with management ■ Comprehensive—measures raw material use, waste generation and production on daily basis ■ Integral to business decisions: pricing, improvement projects	**Negative Attributes** ■ Data collection is labor intensive ■ Paper-based—all of the data used in measurement come from paper records rather than computerized information systems
Lucent Technologies—Integrated software generates reports on demand. Tracks process, cost, chemical use data.	
Positive Attributes ■ System integrates existing data in various databases: no new data collection required ■ Design allows manufacturing staff to improve production ■ Data automatically updated ■ Hazardous and nonhazardous materials tracking	**Negative Attributes** ■ Does not track waste ■ Data not used at corporate level ■ Labor-intensive installation and setup of system; proprietary to Lucent
IBM—P2 measurement calculated by EHS staff using data generated from various databases.	
Positive Attributes ■ Takes into account changing nature of product; makes cross-facility comparisons possible ■ No new data requirement ■ Off-spec product is not counted in output, so quality improvements are reflected in P2 measurement	**Negative Attributes** ■ Reactive—only gives feedback at the end of the year rather than providing feedback to operations during the year ■ Tracks only hazardous waste reductions—not improved efficiencies of chemical use
Wyeth Ayerst—P2 Performance Tracking System.	
Positive Attributes ■ Makes cross-facility comparisons possible ■ No new data requirements ■ Off-spec product is not counted in output, so quality improvements will be reflected in P2 measurement	**Negative Attributes** ■ Paper-based—all of the data used in measurement come from paper records rather than computerized information systems ■ Reactive—system only generated data at the end of the year rather than providing feedback to production operations during the year
Erving Paper—Statistical Process Control-Type System.	
Positive Attributes ■ Simple measure for straightforward process ■ Comprehensive—measures hazardous and nonhazardous raw material use, waste, and production on a daily basis ■ Meets multiple environmental management needs—e.g., Toxics Use Reduction Act (TURA) and Reasonably Achievable Control Technology (RACT) reporting ■ Integral to business decisions—data used to diagnose production quality problems to track high-cost materials ■ Incorporates quality—off-spec product not included in output, so quality improvements will be reflected in P2 progress measure	**Negative Attributes** ■ None observed

- Weekly change in number of rejects per plating barrel or rack or per pieces plated.

Management at Greene started charting all rejects by type or reason. Brad Crowe, manager, states: "if we measure it, then we can fix it." The quality figures are scrutinized by management and posted at the entrance to the manufacturing floor. According to the staff person in charge of generating the production charts, "People on the line and the lab technicians are sensitive to the [quality data]—it's personal to them. If they see a reject, they want to do something about it . . . they almost take quality problems personally." As a result, Greene has improved its key quality metric (durability of part as measured by salt spray hours).

In addition to tracking rejects, Greene's measurement system tracks raw material use (hazardous and nonhazardous), waste (hazardous and nonhazardous), and daily production levels.

Careful tracking of plating bath life is also a part of Greene's quality program. They are concerned with obtaining the maximum number of parts possible before they need to change a bath, but they also are concerned with finding the point at which the bath is so exhausted that the reject rate increases. Greene has increased its chromium bath life from 20,000 square feet plated before dumping the bath to being able to plate 65,000 square feet before dumping. This accomplishment was achieved by carefully tracking number of square feet plated and quality of resultant parts to determine the maximum bath life.

Greene staff said that even their chemical vendor was shocked that the bath would last that long. Since the chromium bath accounts for 85% of the chemical costs of the plating line, this was a significant savings. Nevertheless, Greene does not routinely calculate the savings achieved by its P2 and quality control efforts.

3.1.2 How the P2 Measurement System Is Used

Greene's P2 program began as a quality program and still is motivated as much by quality concerns as by concerns about costs of waste or costs of raw materials. The pollution prevention activities that Greene is most concerned with are reducing its reject rate[1] and reducing use of costly plating chemicals. The P2 measurement system is therefore used by manufacturing to target and track efforts to reduce quality defects, and chemical use, as well as tracking waste reduction.

The results of P2 measurements at Greene are broadly communicated. Weekly/monthly chemical use and waste per unit-of-output are posted for employees to see and are reviewed continuously by supervisors, the lab, and production management. The P2 measurement system is thus used as a driver for continuous improvements as well as a way to track past efforts.

The P2 measurement system is used to estimate pricing for different jobs. It allows Greene to know costs associated with any given part that they coat or plate.

When Greene's measurement system fails to meet a new information need, the company modifies the system. For example, when production in the powder coating line increased dramatically, waste also increased dramatically due to changeovers between different colors. To communicate the cost of lost raw material due to color changeovers to production scheduling, Greene instituted a measurement metric. The new metric tracks powder changeover waste

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[1]Improved quality control and reduced reject rate is sometimes not thought of as a P2 issue. But reductions of off-specification product reduce the quantity of materials that needs to be disposed of and reduce quantity of inputs that a firm needs to purchase.

pounds per total pounds of paint used. The production scheduling group has used the metric to set and achieve raw material cost and waste generation reduction goals.

3.2 Lucent Technologies, Merrimack Valley, Massachusetts

Lucent Technologies' Merrimack Valley site (formerly AT&T) is a large manufacturer of hybrid circuits, circuit packs, and other computer equipment. For this case study, we focused on the semiconductor fabrication operations. These operations involve processing a silicon substrate through a multistep process. The basic process involves applying a pattern onto the substrate by laying down the pattern for the circuit and either etching the pattern into the substrate or plating the circuit onto the substrate. A resistant coating is used to define the pattern of the circuit and is then stripped from the substrate once the circuit is defined. A substrate may make many passes through different etch and strip processes as layers of circuitry are built up on it.

3.2.1 Description of Facility P2 Measurement System

Lucent Technologies' Merrimack Valley Plant began to develop a production-adjusted measurement of facility P2 as a response to requirements to report under Massachusetts' Toxics Use Reduction Act (TURA), which requires that facilities report a unit-of-product along with quantities of chemical use and waste reduced. They found that it was labor intensive to manually calculate a unit-of-product and consumption every year, so the plant had AT&T Bell Labs work on a software package that integrates data from production lines, corporate systems, and facility-level systems to generate the TURA-required measure. The resultant software tracks the number of substrates that go through different production process steps and uses "number of substrates processed" as the unit-of-product with which to adjust P2 measures. This unit-of-product measures the number of passes that a given substrate makes through process steps rather than merely measuring the number of hybrid circuits that are produced. Not all hybrid circuits require the same number of passes through different process steps. The Lucent software uses an existing bar-code scanning system to calculate the number of passes that substrates make through production processes.

> The process of developing and implementing Lucent's P2 measurement system had other benefits including putting valuable information about costs and chemical use into the hands of process engineers.

Lucent Technologies set up separate measurements of P2 for each of its 10 production units. In hybrid circuit fabrication (the area we focused on for this case study), Lucent uses the number of substrates processed as the unit-of-product with which to adjust P2 measurement. They measure annual reductions in usage of SARA chemicals and hazardous waste per number of substrates processed.

The software that was developed to generate Lucent Technologies P2 has the following characteristics:

- **Data are automatically updated weekly.** This allows engineers and managers to keep up with maintaining accurate measures of P2 even when process lines and products are changing often.
- **Data on materials.** The UNIX-based software is linked to both site and corporate data tracking systems, including material

safety data sheets (MSDSs) and production-related data. This provides relatively simple access to complex sets of information about a particular product as well as a comprehensive view of waste reduction in different process lines.

- **Product data.** The P2 measurement software tracks the number of substrates that go through different production process steps using the existing bar-code scanners at the facility.
- **Cost data** are obtained from an existing on-site cost tracking system.
- **Data collection from automated barcode system** allows for efficient measurements of different product lines.

3.2.2 How the P2 Measurement System Is Used

Merrimack Valley's P2 measurement system is driven by the need to report to the State of Massachusetts on reductions in hazardous waste and chemical use under the State's TURA. These measurements are calculated only once a year.

However, Lucent found that the process of developing and implementing their P2 measurement system had other, more immediate, benefits. Chief among these benefits was the new ability of facility engineers to access the following types of information:

- Production quantities,
- Withdrawal of chemicals from a central storeroom,
- Yield information,
- Design information on the product,
- Information on how a specific hybrid circuit moves through the product line, and
- Cost of product at any stage of its production.

Engineers can click on any data outlier (e.g., excessive use of a chemical) and find out what products were going through the process at that time and find design information on those products. This is a powerful way of understanding process fluctuations and minimizing variations in process conditions. Thus, the need for P2 measurement resulted in installation of a system that allowed better process control and better understanding of process costs as well as better tracking of P2 projects.

Not all of the process engineers take advantage of this information, and the menu-driven software was unfamiliar to some of the engineers. But others have taken to the system "like ducks to water," according to the environmental engineering department. Three examples of how the system has been used by process engineers are for targeting chemical use reduction efforts, to target change in operational strategies, and to demonstrate P2 results on a given process line.

3.3 IBM, Burlington, Vermont

The IBM Burlington facility employs 6,600 employees in manufacturing memory, logic, and specialty chips using 1, 4, and 16 Mega-bit technology. The manufacture of memory and logic chips involves roughly 70 to 100 distinct production steps. Wafers begin as raw silicon and are processed through a variety of diffusion, ion implantation, photolithography, etching, metalization, and deposition steps before being diced into individual chips. These chips are then

> IBM's P2 measurement system is important to stakeholder communication.

mounted in modules and sold to internal (IBM) and external customers.

3.3.1 Description of Facility P2 Measurement System

IBM developed their P2 measurement system in response to a desire at the corporate level to track P2 progress and a concern that existing measures of P2 might not accurately reflect progress in the highly dynamic semiconductor industry. The company's major concern in developing a P2 measurement method was to ensure that it not only accurately captured reduction in waste but also captured the many improvements in IBM's products from year to year. This is important to a semiconductor manufacturer because from year to year a manufacturer produces products that remain descriptively similar like "chips" and "modules," but the products nevertheless increase in complexity so much that they are functionally not the same product from year to year. The dynamic nature of IBM products makes measurement of P2 progress for the company difficult. IBM therefore developed a combined "performance index" that consists of a weighted aggregate of the total number of bits, total number of circuits, and total number of masks produced. The numbers of bits, circuits, and masks are weighted by the contribution they made to sales from the facility. This performance index is the unit-of-product with which IBM adjusts its P2 measurements.

One criterion for the development of IBM's P2 system was that it must use existing data, but in the past year a question has arisen as to whether the necessary information for the current system would continue to be available. This potential problem arises from the fact that the IBM system (like many of our case study systems) relies on data collected by departments for preexisting purposes. If the original purpose for collecting the data is eliminated, then the data will have to be collected exclusively for the purposes of P2 measurement.

3.3.2 How the P2 Measurement System Is Used

The primary purpose of IBM's P2 measurement is stakeholder communication. IBM makes its measurement of P2 on an annual basis and provides that information to government regulators. Since the P2 measurement system had not been instituted IBM-wide in 1995, it was not included in the IBM 1995 Corporate Environmental Report.

3.4 Wyeth-Ayerst, Rouses Point, New York

Wyeth-Ayerst is a division of American Home Products Corporation, an international Fortune 100 company manufacturing pharmaceuticals and health care products. Our case study site was Wyeth's Rouses Point facility in New York. This site has approximately 1,200 employees. It focuses on production of both prescription and over-the-counter pharmaceutical products In addition, the Rouses Point site handles some nonrecurring laboratory research and development operations.

A major driver at Wyeth facilities is the desire to be the lowest-cost producer of Wyeth products. Rouses Point has implemented a variety of cost containment measures including efforts to reduce cycle time and improve inventory management with a strong focus on production costs.

> Wyeth wanted to be able to assess the success of their P2 programs. Gross waste/emission data do not provide a clear enough picture of the firm's progress.

3.4.1 Description of Facility P2 Measurement System

Wyeth's internal "P2 Performance Tracking System" measures P2 at the division level. For its manufacturing operations, Wyeth uses kilograms of product as the unit-of-product with which to calculate a production-adjusted measure of P2. For its laboratory operations, number of hours worked by staff is the unit used.

3.4.2 Uses of Facility P2 Measurement System

At a corporate level, Wyeth wanted to be able to assess the success of their P2 programs, and gross waste/emission data do not provide a clear enough picture of the facility's progress. Therefore, they developed their internal "P2 Performance Tracking System."

Annually, corporate environmental staff collect hazardous waste data from Wyeth facilities in the United States. They then calculate production-adjusted measures of P2 for each division and use these figures to write a corporate annual P2 report. This is distributed to approximately 100 people at all facilities, including associate engineers, operations managers, environmental managers, and research managers. The P2 Performance Tracking System is not used by site personnel to improve operations on a day-to-day basis.

3.5 Erving Paper, Erving, Massachusetts

Erving Paper is a privately owned manufacturer of absorbent paper towels, tissues, wrapping paper, and printed napkins. The company employs 300 people at three facilities in Miami, Florida; Green Bay, Wisconsin; and Erving, Massachusetts. The Erving facility employs 150 people and operates 7 days per week, 52 weeks per year.

> Erving's measurement system evolved from its quality assurance program. The data help the firm spot process problems as well as comply with environmental regulations.

The Massachusetts facility operates continuously. Their process involves pulping used paper, and bleaching the pulp. During the pulping and bleaching process, sodium hydroxide and sulfuric acid are used to modulate the pH of the pulp for optimal results. The pulp is then distributed onto screens and conducted through rollers and driers to produce rolls of recycled paper. These rolls undergo further finishing at the Erving Paper facility or are sold directly to customers.

3.5.1 Description of Facility P2 Measurement System

Erving's measurement system evolved from its quality assurance program. Erving measures P2 by looking at chemical use reduction as well as waste reduction. The production and chemical use data that Erving uses to generate P2 measurements were originally collected as part of the company's statistical process control (SPC) program. The data were used to determine process trends, reduce process variation, and allow for greater operator control over the process. While no longer used for that purpose, the data are still collected and used by the manufacturing and environmental departments.

Chemical use is measured each morning by either measuring levels inside tote tanks or reading meters on pumps dedicated to specific bulk tanks. Tote tank measurements are converted from changes in the level in the tank in inches to gallons used per day. Chemicals are measured at the following intervals:

- Bulk Chemicals—use measured daily—alum, sodium hypochloride, sodium hydroxide, sulfuric acid, and wet strength resin;
- Tote Chemicals—use measured daily—antifoam chemical, continuous felt cleaner (proprietary cleaner—aliphatic hydrocarbon with approximately 10% emulsifier), antidusting agent, solvent, optical brightener; and
- Low-volume/low-cost chemicals—use measured bi-weekly.

Production is measured each day in pounds of paper. Erving's product may vary in brightness or weight, but the qualities of paper are not significantly different from the standpoint of chemical use or waste production. Pounds of off-spec paper are also measured daily.

3.5.2 Uses for the P2 Measurement System at the Facility

The chemical use data collected under Erving's P2 measurement system are no longer used for SPC. However, the use data are reviewed by Erving's Technical Director, who looks for large daily variations. This allows Erving to spot problems such as pump failure or operator error and helps Erving target parts of their process for cost control. Chemical use data are also used to determine when to reorder chemicals to fill depleted storage tanks. The use data also give them the information they need to comply with their State air pollution reasonably achievable control technology (RACT) requirements, State TURA reporting, and Federal TRI reporting.

Section 4
Results Obtained by Correlating the Production-Adjusting Units Used and Pollution or Chemical Use for the Five Case Study Sites

The primary focus in this project was to identify and verify how well the unit-of-product used in pollution prevention measures at our five case study facilities explained variation in key waste streams or chemical usage at the facility. In doing so, we were able to provide a preliminary indication of the usefulness of that unit-of-product in similarly situated facilities.

For each system we looked at, we applied the method of analysis presented in Section 3. This provided insight into the unit-of-product that the facility uses to measure P2. This analysis achieved two objectives:

1. Provided the case study facilities with a better understanding of their measurement accuracy; and
2. Tested the application of the statistical and graphical verification method using real rather than hypothetical data.

In this section, we present the results of the verification of the different units-of-product (i.e., how well they explained variations in chemical use and chemical waste). The units-of-product that we analyzed are summarized in Table 4-1.

4.1 Greene Manufacturing Company, Inc.

RTI and Greiner Environmental examined the correlation between Greene Manufacturing Company's unit-of-product and two high-volume chemicals—zinc and sodium cyanide. The investigation was done for the firm's two major metal plating operations—the rack line and the barrel line. Greene uses square feet plated as its unit-of-product.

The analysis found that both zinc and sodium cyanide were strongly correlated with square feet plated for both the rack and the barrel line.

4.1.1 Data Collection

In November 1995, RTI and Greiner Environmental researchers visited the Greene Connorsville site to observe the operation and collect data for the study. Greene provided RTI with data on daily chemical consumption and square feet processed for the company's rack, barrel, anodizing, and phosphatizing lines. We performed unit-of-product analysis on two major chemicals (sodium cyanide and zinc) used in the rack and barrel electroplating lines.

Chemical Data. Greene provided chemical data for the years 1994-95. The chemical data came from quality control records of chemical additions to the process baths.

Production Data. Greene provided daily data for the number of square feet plated on the rack and barrel plating lines.

4.1.2 Data Analysis

The analysis for Greene data examined the correlation between chemical use (zinc and sodium

Table 4-1. How Well Units-of-Product Explained Variation in Chemical Use and Waste Generation

Industry	Unit-of-product used for adjusting pollution-prevention measurement	Did unit-of-product explain variations in: Chemical use for key inputs?	Did unit-of-product explain variations in: Waste generation for key waste streams?	Facility or company-wide measure or process specific?
Metal finishing	Square feet substrate plated or coated	Yes	NA[a]	Process-specific
Paper recycling	Tons of paper produced	Yes	NA	Facility-wide
Semiconductor fabrication	Combined unit-of-product incorporates number of memory chips, logic chips, and masks produced [as surrogate for technological content of product]; number of module parts produced	Combined unit-of-product correlated for some chemicals, not for others; module parts correlated for all chemicals[b]	Number of bits (a component of the combined unit-of-product) correlated with one waste stream; module parts correlated with same waste stream[b]	Facility-wide
Electronics production	Number of passes substrate makes through process	Yes	NA	Specific to each product line
Pharmaceutical production	Kilograms of product produced	Yes	Yes	Specific to individual department

[a] NA = Not applicable.
[b] Results somewhat uncertain; see Section 4.3.3 for full discussion.

cyanide) and Greene's unit-of-product (square feet plated).

Rack Line—Zinc and Sodium Cyanide. The histograms of weekly pounds zinc and pounds sodium cyanide use adjusted by square feet plated are presented in Figures 4-1 and 4-2.

Note that both figures have normally shaped distributions. Time series plots were also prepared to see the variation in chemical use per 1,000 square feet plated over time. All things being equal, one would expect a random time series pattern—as opposed to an increasing pattern or decreasing pattern.[2] The time series plots in Figures 4-3 and 4-4 both have random patterns.

Lastly, scatter plots of square feet plated on the x and chemical use (pounds of sodium cyanide and zinc) on the y-axis were prepared (Figures 4-5 and 4-6). Best-fit regression lines were

[2]Constantly increasing or decreasing trends are indicative of unstable processes. It would be next to impossible to find a correlated unit-of-product for an unstable process.

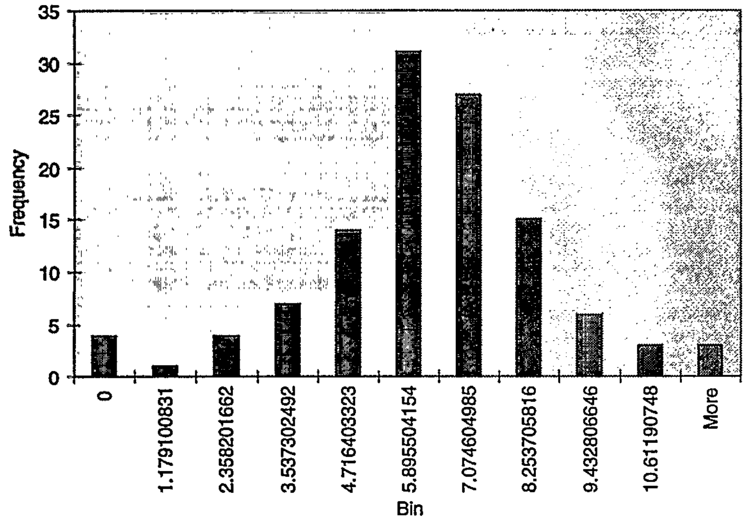


Figure 4-1. Weekly pounds of sodium cyanide per 1,000 ft^2 plated histogram (rack line).

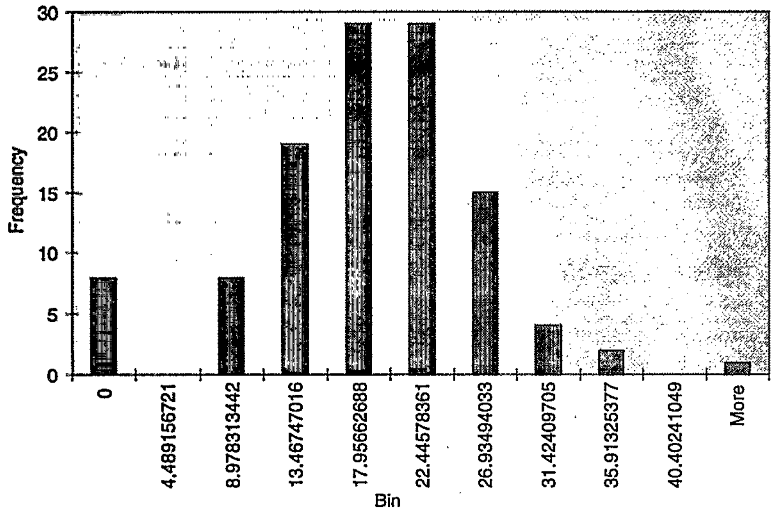


Figure 4-2. Weekly pounds of zinc used per 1,000 ft^2 plated histogram (rack line).

added to each scatter plot as were R-squared values and equation for the line. Greater R-squared values, i.e., closer to 1.0, are indicative of greater correlation. The scatter plots and regression lines indicate that both sodium cyanide and zinc usage are correlated with square feet plated. The Figure 4-5 linear regressions R-squared statistic equals ~0.74—inferring that square feet plated accounts for 74% of the variation in sodium cyanide use.[3] The equation of the line ($y = 6.24x + 8.42$) indicates that over the 24-month time period 1994-95, the average pounds of sodium cyanide use per 1,000 square feet plated equals 6.24.

Researchers found a disturbing pattern among the regression residuals for both sodium cyanide and zinc (see Figures 4-7 and 4-8). Standard statistical practice requires that regression residuals have a constant, non-spreading pattern. A spreading pattern can negate a regression analysis' results. The residuals in Figures 4-7 and 4-8 become more negative and more positive as the number of square feet plated increases.

Researchers felt that the spreading pattern was due to the tremendous variation in the weekly production and chemical use data—and decided to examine monthly use and production data to see if they also exhibited the spreading pattern. Analysis of monthly data eliminated the residual spreading pattern—see

[3]These regression results are statistically significant. The P-value for the slope of the regression (pounds of NaCN use per millions of modules) equals 1.1E-34. P-values <0.05 are generally considered statistically significant. The P-value tells us that we can be 99.99% confident that the relationship between cyanide use and square feet plated is not random.

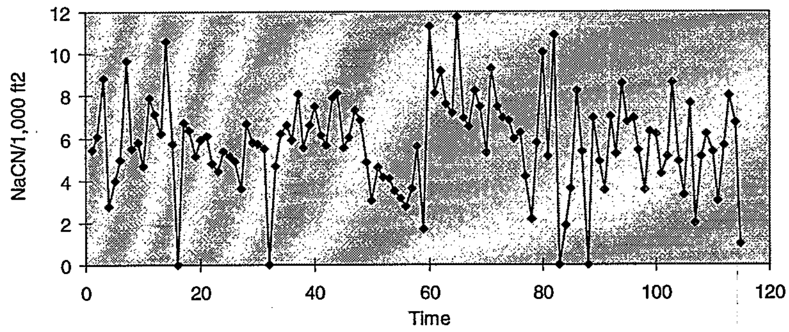


Figure 4-3. Weekly pounds of sodium cyanide used per 1,000 ft^2 plated time series plot.

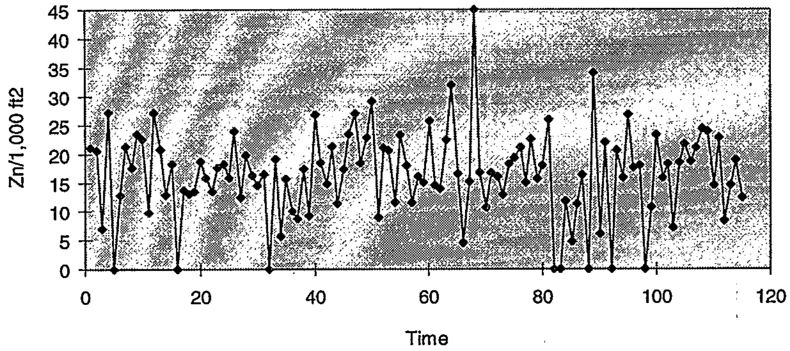


Figure 4-4. Weekly pounds of zinc per 1,000 ft^2 plated time series plot.

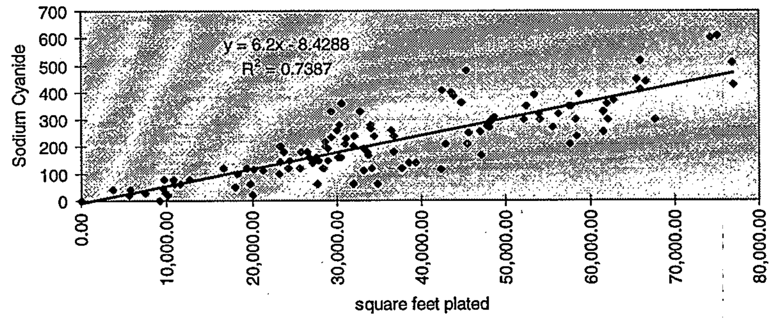


Figure 4-5. Scatter plot showing relationship between weekly pounds of sodium cyanide and square feet plated (rack line).

scatter and residual plots for sodium cyanide and zinc in Figures 4-9 through 4-12.

In summary, square feet plated is strongly correlated to both sodium cyanide and zinc. Monthly data produced similar results as weekly data but without the problem of spread in the regression residuals.

Barrel Line Analysis. Graphical methods were also used to examine the correlation between two barrel line chemicals (sodium cyanide and zinc) and square feet plated. Histograms of monthly use data per 1,000 square feet plated are presented in Figures 4-13 and 4-14. Both histograms appear to be bell-shaped—an early indication that correlations for both chemicals are likely to be strong.

Time series plots of monthly barrel line sodium cyanide and zinc were also prepared. Note the large increase in both sodium cyanide (Figure 4-15) and zinc (Figure 4-16) per 1,000 square foot plated in June 1995. The June 1995 data points corresponded to several weeks during which Greene did little, if any, plating, leading to low efficiency of use.

Scatter plots with thousands of square feet plated on the x-axis and sodium cyanide and zinc on the y-axis were also prepared (Figures 4-17 and 4-18). Best-fit regression lines were added to

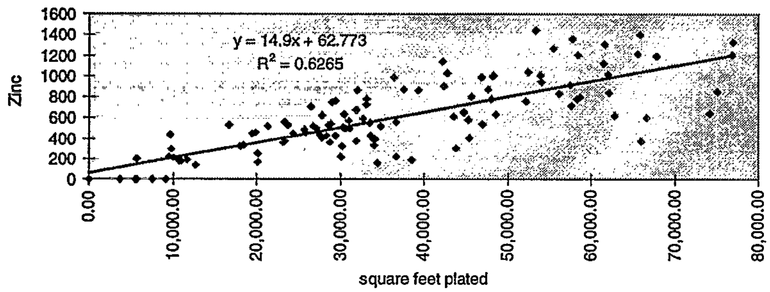


Figure 4-6. Scatter plot showing relationship between pounds of zinc and square feet plated (rack line).

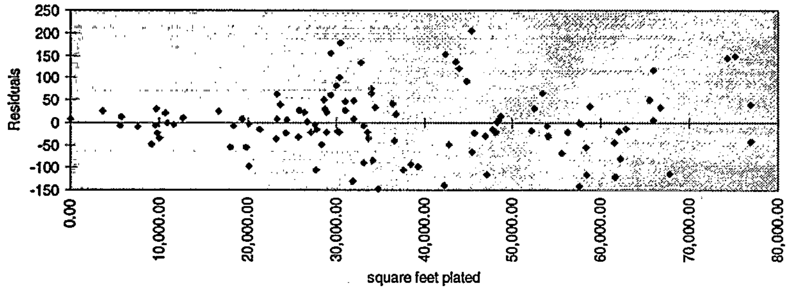


Figure 4-7. Weekly pounds of sodium cyanide per square foot plated residual plot (rack line).

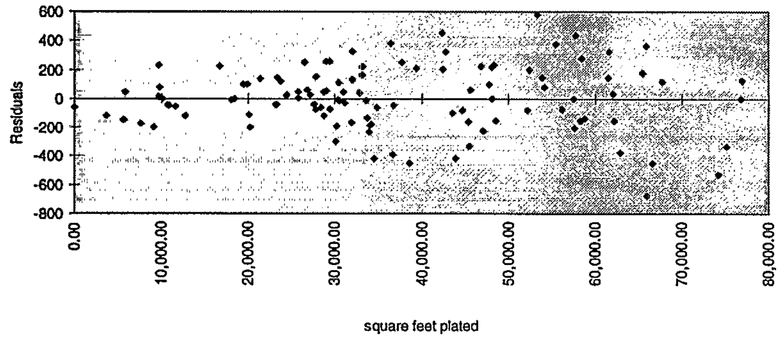


Figure 4-8. Weekly pounds of zinc per square foot plated residual plot (rack line).

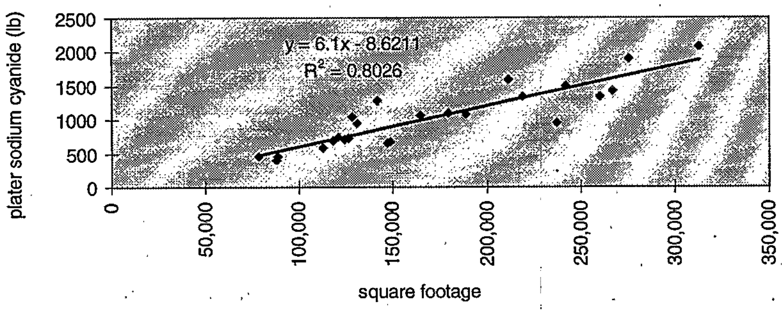


Figure 4-9. Monthly pounds of sodium cyanide per square foot plated scatter plot (rack line).

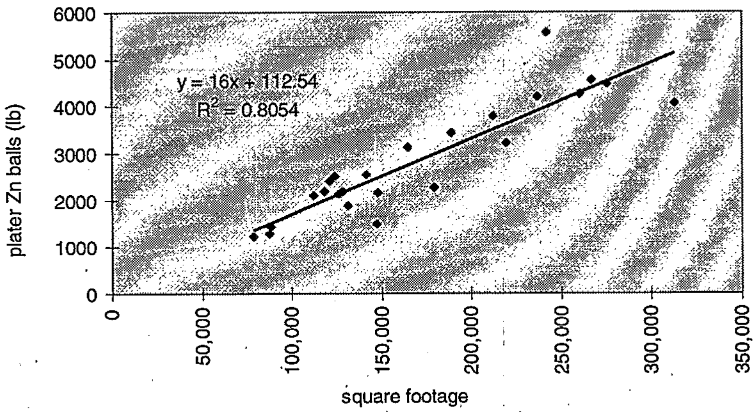


Figure 4-10. Monthly pounds of zinc per square foot plated scatter plot (rack line).

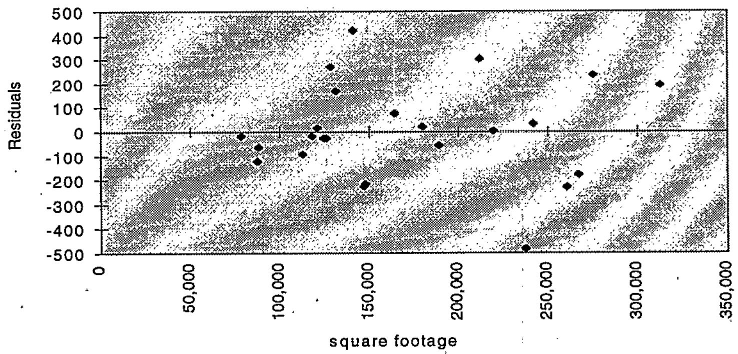


Figure 4-11. Monthly pounds of sodium cyanide per square foot plated residual plot (rack line).

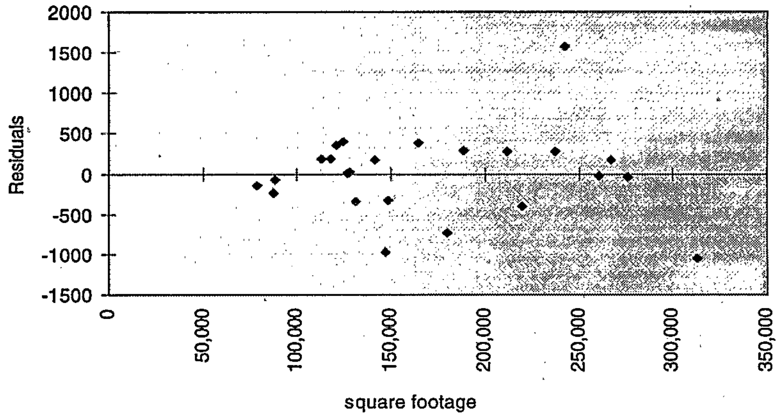


Figure 4-12. Monthly pounds of zinc per square foot plated residual plot (rack line).

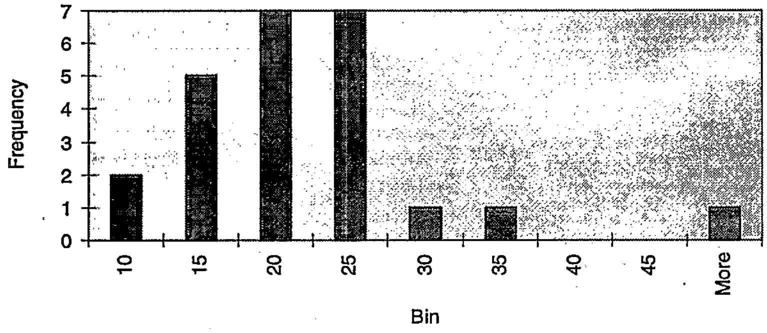


Figure 4-13. Monthly pounds of sodium cyanide per square foot plated histogram (barrel line).

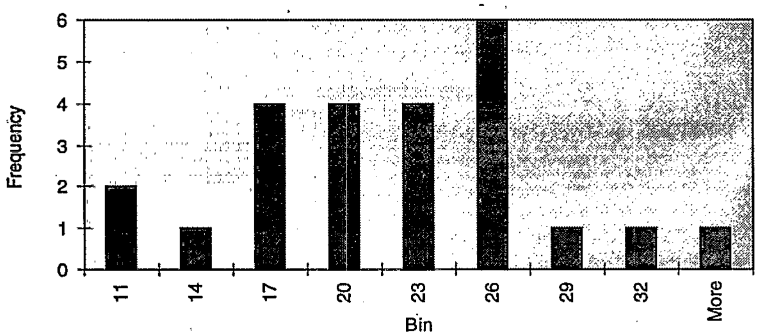


Figure 4-14. Monthly pounds of zinc per square foot plated histogram (barrel line).

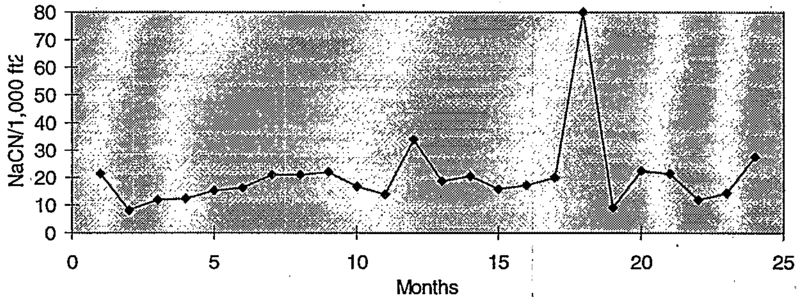


Figure 4-15. Monthly pounds of sodium cyanide per square foot plated time series plot (barrel line).

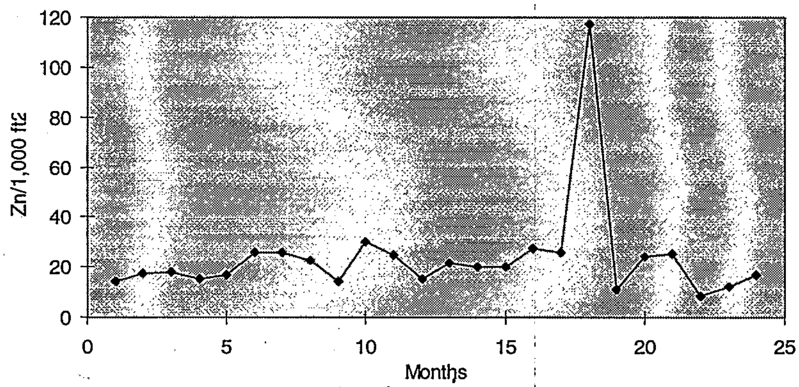


Figure 4-16. Monthly pounds of zinc per square foot plated time series plot (barrel line).

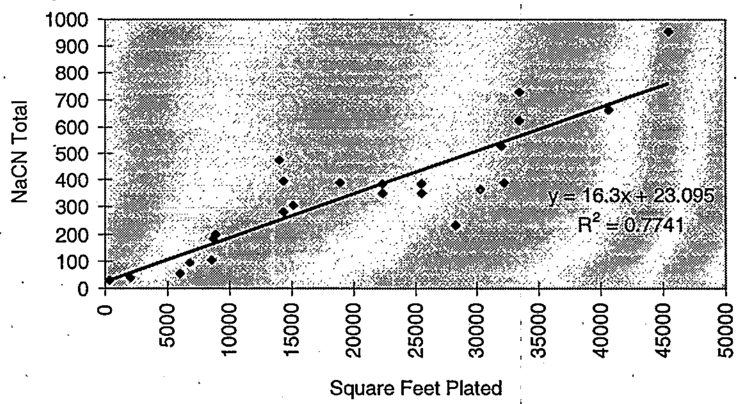


Figure 4-17. Scatter plot showing relationship between monthly sodium cyanide use and square foot plated (barrel line).

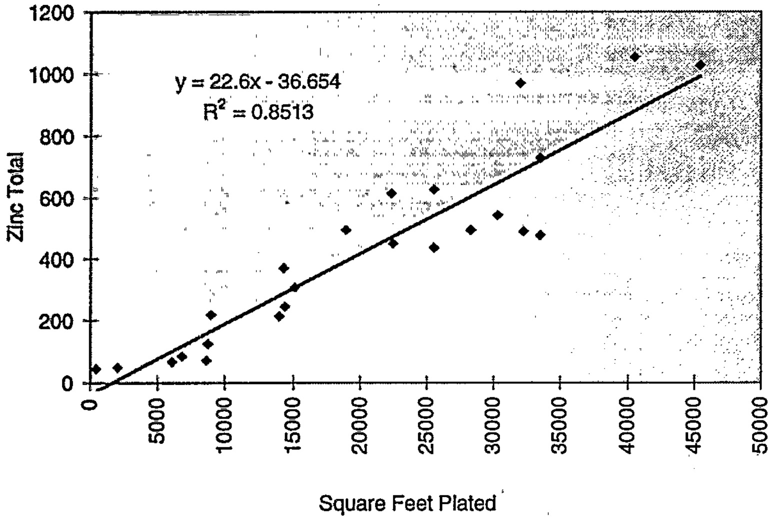


Figure 4-18. Scatter plot showing relationship between monthly zinc use and square foot plated (barrel line).

each scatter plot as were R-squared values and an equation for the line.

The scatter plots and regression lines indicate that square feet plated is strongly correlated with both sodium cyanide and zinc (R-squared and P-values are 0.77 and 1.5E-08 for sodium cyanide and 0.85 and 1.4E-10 for zinc). Residual plots of monthly data for both chemicals have random patterns.

4.1.3 Findings

The unit-of-product, "square feet plated," is strongly correlated to chemical use for the two chemicals analyzed in this study. This is true for both process lines examined.

4.2 Lucent Technologies

We followed the four-step data analysis procedure outlined in Section 3 for the data provided to us by Lucent Technologies. For the purposes of examining the unit-of-product, we used data from two of the semiconductor process lines.

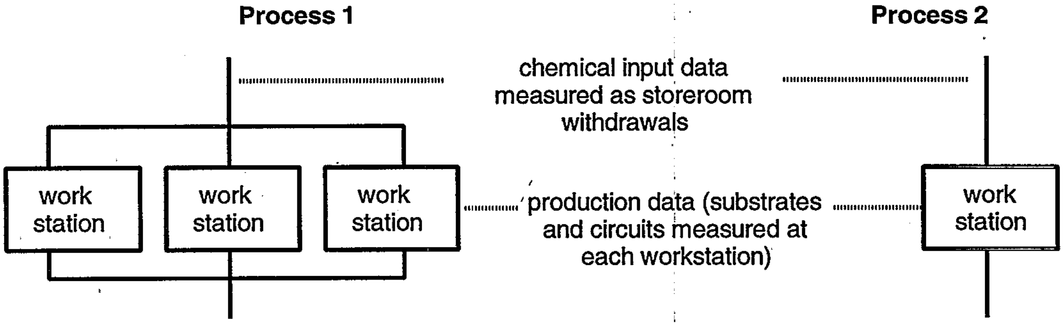
Lucent Technologies provided chemical use and production data on two production processes that remove the photo-resist from a Lucent Technologies product. Process 1 is Lucent's high-volume line. This high-volume line has three identical workstations. Process 2 is Lucent's low-volume production line. It comprises a single work station. Lucent uses substrates produced as the unit-of-product to adjust measurements of change in glycol ether use in both processes (Box 4-1).

Chemical Use Data. Weekly glycol ether data were not available since use is not measured at the process level. Instead Lucent Technologies provided the withdrawal data for photo-resist stripper which contains 55% glycol ether from the chemical storage area for each process. Because a small amount of chemical remains in inventory either in the process or stored near the process, weekly chemical withdrawals represent an estimate of weekly chemical use.

Production Data. Weekly production data (number of circuits and number of substrates) were available for each process (and for each Process 1 workstation). Lucent Technologies defines a substrate as the number of passes a "widget" makes through a workstation. If the same widget makes three passes through a workstation, throughput through the process equals three substrates. Lucent Technologies defines circuits differently. The number of circuits on a widget is constant—no matter how many times a widget passes through a workstation, the number of circuits on it remains

Box 4-1.

Sources of Data for Analysis of Lucent Unit-of-Product



unchanged. For example, if a widget has two circuits on it and the widget passes through a workstation three times, throughput through the process equals two circuits.

Data Entry. Weekly data were entered into an Excel spreadsheet in the following manner:

- Week of year for 1994;
- Gallons of photo-resist used each week (taken out of chemical storage);
- Process 1: number of substrates produced each week for the three work centers;
- Process 1: number of circuits produced each week for the three work centers;
- Process 2: number of substrates produced each week; and
- Process 2: number of circuits produced each week.

Data Manipulation. Data were manipulated to generate basic measures of process efficiency (Table 4-2). The following manipulations were performed:

- Convert gallons of photo-resist stripper used per week to pounds of glycol ether used per week (stripper is 55% glycol ether at 9.174 lb/gal);
- Divide weekly chemical use by weekly production (e.g., glycol ether pounds used per substrate manufactured); and
- Calculate 1994 average pounds of chemical use per unit-of-output (e.g., number substrates processed and number circuits produced).

How do Process 1 and Process 2 compare in chemical use efficiency? Using number of substrates processed to adjust glycol ether use, Process 1 is more chemical use efficient than Process 2: 23.4 lb glycol ether/substrate versus 53.1 lb glycol ether/substrate. Using circuits to adjust the data, the two processes appear to have equivalent chemical use efficiencies: 5.0 lb glycol ether/circuit versus 6.3 lb glycol ether/circuit.

Although our two metrics give different results, Lucent engineers believe that substrates are a better unit-of-product than circuits since substrates count the number of passes a product might make through the operation. Furthermore, Process 1 is a high-volume line while Process 2

Table 4-2. Glycol Ether Use per Unit-of-Product

	Circuits produced	Substrates produced[a]	Glycol ether use
Process 1			
1994 total	13,898,841	2,970,872	69,631
Pounds of glycol ether/1,000 units	5.0	23.4	—
Process 2			
1994 total	640,316	75,499	4,011
Pounds of glycol ether/1,000 units	6.3	53.1	—

[a] Lucent defines substrates as the number of passes a "widget" makes through a workstation.

is a low-volume line—engineers believe the high-volume line is more use efficient because less waste is created during startup and shutdown of the line.

Our analysis thus far raises two interesting questions. First, which factor (substrates or circuits) is a better unit-of-product to adjust P2 measures for Process 1? For Process 2? Second, is Process 1 more use-efficient than Process 2? To answer these questions, the data supplied must be analyzed in greater depth.

4.2.1 Process 1 Analysis

The distribution of the data and descriptive statistics shed light on Process 1's unit-of-product (substrates).

Histogram and Descriptive Statistics. To look at the distribution of the data, a histogram was prepared (Figure 4-19). All but two data points fell into the range between 0 and 60. Two data points were greater than 75. These points had values of 120 and 3,144. Researchers checked to see if the outlier (with a value of 3,144) was due to a data entry error. It was not.

To examine the effect of this outlier, we compiled a set of descriptive statistics (an Excel data analysis option). These are presented as Table 4-3. The descriptive statistics were run on the entire data set (51 weeks) and on the data set with the outlier removed (50 weeks). Note the large change in mean, standard error, standard deviation, and 95% confidence level.

4.2.2 Plot Time-Series and Moving Average

Time series plots of glycol ether use per unit-of-product were generated, using both substrates and circuits as the unit-of-product (Figures 4-20 and 4-21).

Since some glycol ether is in inventory in the workstation and in storage areas on the production floor, a moving average was also calculated and plotted. In this moving average plot, each week's chemical use is the average of the current week and the two preceding weeks. A

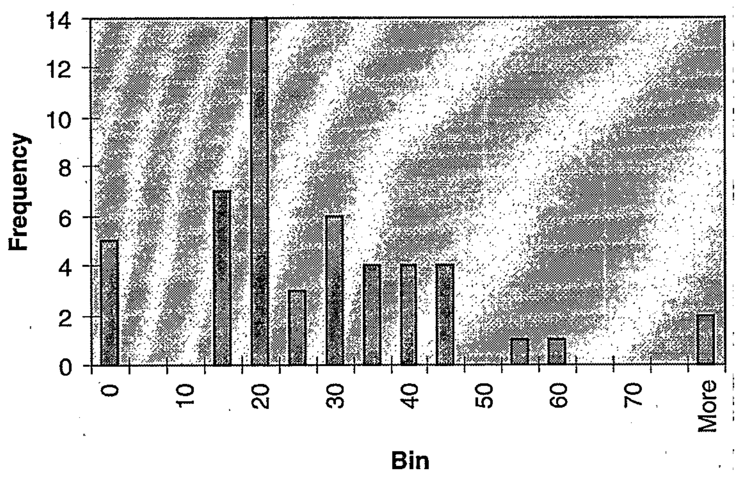


Figure 4-19. Weekly glycol ether use (lb) per substrate histogram (Process 1).

Table 4-3. Process 1 Descriptive Statistics for Glycol Ether Use per Substrate

Glycol Ether Use/Substrate (thousands)	Full data set	Outlier removed
Mean	86	25
Standard error	61	2.7
Median	20	19
Mode	0	0
Standard deviation	437	19
Minimum	0	0
Maximum	3,143	120
Count	51	50
Confidence level (95.0%)[a]	123	5.4

[a] This confidence level indicates that the true mean is 95 percent likely to be between 86±123. This is too large a range to be meaningful. Once the outlier is removed, the data become more manageable.

moving average plot tends to smooth out large swings in a data set.

Figures 4-20 and 4-21 present the time series plot (actual) and moving average plot (forecast) of glycol ether use per substrate and per circuit. Notice that in Figure 4-20 one data point is considerably off the scale. This is the outlier (value = 3,144). The plots indicate that, on the whole, glycol ether use per substrate is fairly constant over time with two exceptions (week 1 and week 36).

We aggregated the weekly data into monthly data and prepared time-series plots and performed regression analyses. The time series plot for both substrates and circuits per unit-of-product are presented as Figure 4-22.

Scatter plots of Process 1 depicting glycol ether use per substrate and glycol ether use per circuit were prepared (Figures 4-23 and 4-24). Best-fit regression lines were added to each scatter plot as were R-squared values and equation for the line. R-squared values closer to 1.0 are indicative of greater correlation.

The scatter plots and regression lines indicate that substrates but not circuits are correlated with glycol ether usage. The Process 1 Substrate Plot linear regression R-squared statistic equals ~0.42 This infers that the number of substrates processed accounts for 42% of the variation in sodium cyanide use.[4] The equation of

[4]These regression results are statistically significant. The P-value for the slope of the regression (pounds of glycol ether use per substrate equals 0.02). P-values <0.05 are generally considered statistically significant. The P-value infers that we can be 99.98% confident that the relationship between glycol ether use and substrates is not random.

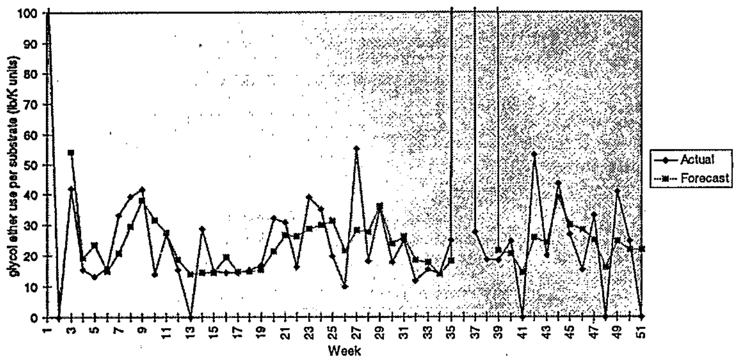


Figure 4-20. Weekly glycol ether use per substrate time-series moving average plot (Process 1).

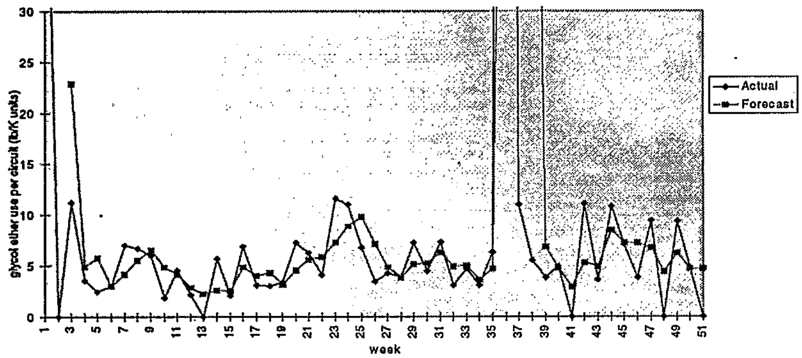


Figure 4-21. Weekly glycol ether use per circuit time-series moving average plot (Process 1).

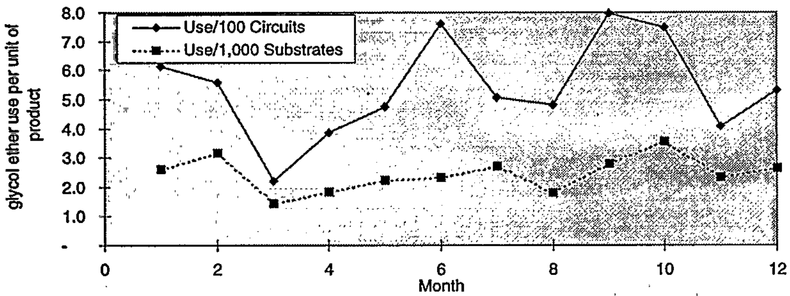


Figure 4-22. Monthly glycol ether use per unit-of-product time series plot (Process 1).

the line (y = 0.0116x + 2,932) indicates that over the 12 months in 1994 the average number of pounds of glycol ether use per substrate equals 0.0116 lb (or 11.6 lb per 1,000 substrates processed).

Process 1 Findings. It appears that substrates processed track glycol ether use well and circuits do not. This result is consistent with the predictions of the Lucent engineers who set up the P2 measurement system. Based on this analysis, using the number of substrates produced will provide Lucent Technologies with an accurate picture of pollution-prevention progress (as measured by change in quantity of glycol ether used) in Process 1.

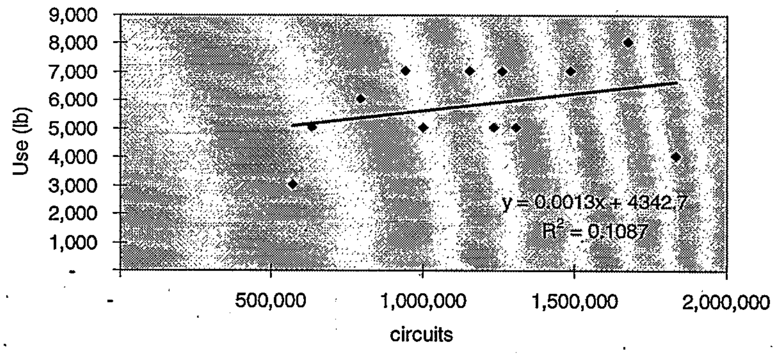


Figure 4-23. Monthly glycol ether use per circuit scatter plot (Process 1).

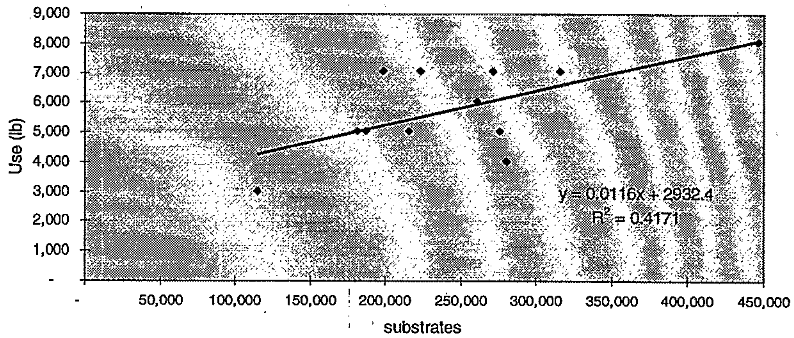


Figure 4-24. Monthly glycol ether use per substrate scatter plot (Process 1).

4.2.3 Process 2 Data Analysis

The next step in the analysis is to review Process 2 data more carefully.

Histogram and Descriptive Statistics. To look at the distribution of Process 2 use/output data, a histogram was prepared (Figure 4-25). Data from Process 2 have greater spread than the data from Process 1. This is because Process 2 is run intermittently and nearly half of the data points had values of zero.

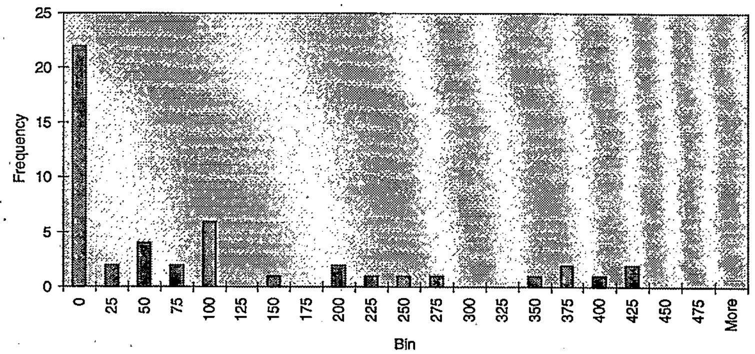


Figure 4-25. Weekly glycol ether use per substrate histogram (Process 2).

Descriptive statistics were applied to the data set (Table 4-4). The large difference between the median and mean indicate the data are not normally distributed, an indication that a correlation between chemical use and unit-of-product will not be found.

Plot Time-Series and Moving Average. Figure 4-26 presents the time series plots (actual) and moving average plots (forecast) for glycol ether use per substrate. Notice that for the first half of the year (first 26 weeks) both actual and forecast glycol ether use per substrate varies from zero to 200 lb/1,000 units. In the second half of the year, however, the variation in use per substrate increases dramatically. One would expect no change in average use per unit of output over time (assuming no major changes to the production process or product runs through the process). This large increase in variation makes using substrates as a normalization factor problematic.

Compare Substrates and Circuits as Adjusting Factors. To examine the difference between substrates and circuits as a unit-of-product, a time series and moving average plot of glycol ether use per circuit was generated (Figure 4-27) in order to compare it to the time-series plot for Process 1 (Figure 4-21). Process 2 substrate and circuit plots exhibit some differences. First, the first data point in the circuit plot has an extremely large value that was not seen in

Table 4-4. Process 2 Descriptive Statistics for Glycol Ether Use per Substrate

Mean	91
Standard error	19
Median	26
Mode	0
Standard deviation	131
Minimum	0
Maximum	424
Count	48
Confidence level (95.0%)	38

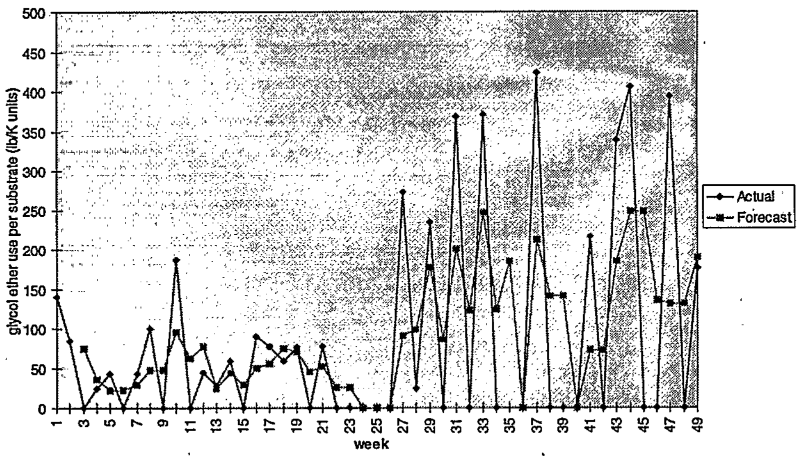


Figure 4-26. Glycol ether use per substrate time-series moving average plot (Process 2).

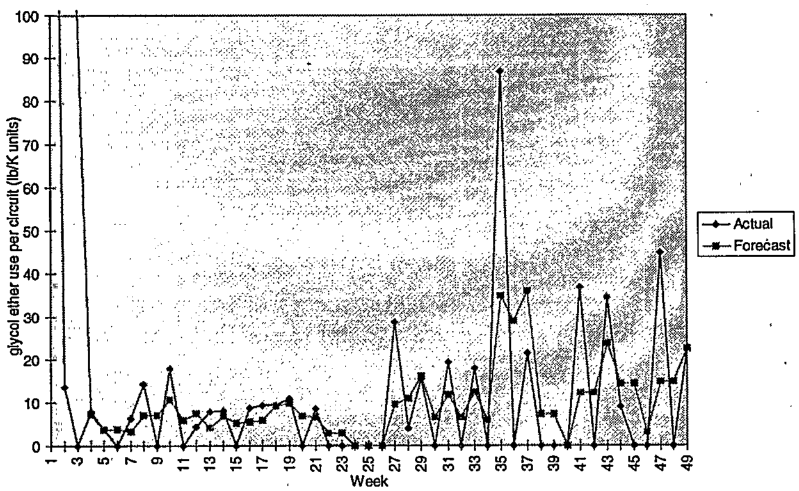


Figure 4-27 Glycol ether use per circuit time-series moving average plot (Process 2).

the substrate plot. Second, while circuit data for the second half of the year vary more than the first half of the year, the increase in variation appears to be less than that seen in the substrate plot.

Scatter plots of Process 2 (low-volume line) depict glycol ether use per substrate and glycol ether use per circuit (Figures 4-28 and 4-29). Best-fit regression lines, R-squared values, and the equation for the line were added to each scatter plot. R-squared values closer to 1.0 are indicative of greater correlation.

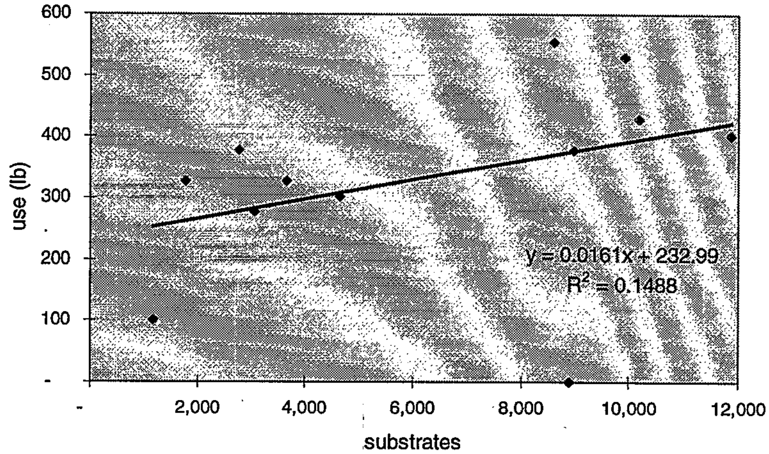


Figure 4-28. Glycol ether use versus substrates scatter plot (Process 2).

Process 2 Findings. Because glycol ether use per substrate per circuit changes significantly halfway through the year, neither metric could be characterized as well-correlated normalization factors.

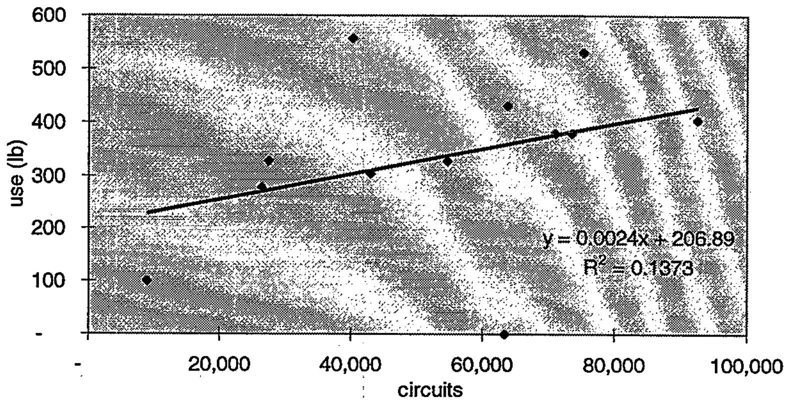


Figure 4-29. Glycol ether use versus circuits scatter plot (Process 2).

4.2.4 Findings

Lucent's data analysis pointed out that Process 1's unit-of-product used to adjust pollution-prevention measures accurately reflects P2 progress. Process 2's unit-of-product does not measure pollution-prevention progress accurately. The data analysis also brought out the following points:

- Despite not having actual use data, we were able to qualitatively determine the accuracy of Lucent's normalization factors.
- The analysis revealed that for Process 1 substrates processed are a good production-adjustment factor. Readers will recall that substrates processed are equal to the number of passes through a workstation that a given product makes. Number of circuits did not correlate well with glycol ether use.
- The analysis revealed unexpected results—Process 2's chemical use per unit-of-product increased in the second half of 1994.
- The analysis can act as a process diagnostic tool—engineers could return to Process 2 and find out why chemical use efficiency declined in the second half of 1994.

4.3 IBM, Burlington, Vermont

RTI and Greiner Environmental worked with staff at the IBM Burlington facility to assess two possible units-of-product for the facility.

The first unit-of-product analyzed was IBM's performance index which it uses for tracking P2 progress. The performance index consists of an aggregate of bits,[5] circuits,[6] and masks data weighted by percent revenue. We used IBM data to construct a modified version of the performance index, using number of bits and number of circuits, weighted by percent revenue. IBM's performance index is used to assess P2 progress on an annual basis. The analysis here uses monthly figures, since there were inadequate annual data to conduct the analysis (see Section 2.2 on the topic of number of data points).

The second unit-of-product examined was number of modules. The analysis examined how well number of modules explained chemical usage and generation of one waste stream. Modules are the final mounted chips, and there are both bits and circuits on these mounted chips. This alternative unit-of-product does not account for the changing complexity of the IBM products.

4.3.1 Data Collection

Chemical Data. IBM provided data for monthly SARA 313 chemical use over a two calendar-year period 1993-1994 (Table 4-5). IBM uses a computerized tracking system to monitor all

Table 4-5. Chemical and Production Data Provided by IBM

Chemical Data[a]	Production Data[b]
1. IPA (isopropyl alcohol) use	1. Number of modules manufactured
2. Xylene use	2. Performance index
3. Ethylbenzene use	3. Number of bits manufactured (memory product)
4. Cyclohexanone use	
5. PGMEA use	4. Number of circuits manufactured (logic product)
6. NBA (*N*-butyl acetate) use	
7. NMP (*N*-methyl-2-pyrrolidone) use	
8. Total of seven chemical uses listed above	
9. PGMEA/cyclohexanone waste stream (IBM internal waste stream #38)	

[a] Chemical use data were Chemical Abstract System (CAS) number, monthly, pound totals for each chemical for 1993 and 1994. Chemical waste generation data were monthly shipment and beginning and ending inventory data from the Chemical Distribution Center which manages both chemicals and waste.

[b] Production data were monthly totals for 1993 and 1994. The performance index is a combination of bits manufactured and circuits manufactured weighted by the percent revenue from each product.

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[5] Bits are the measure of production for memory products.

[6] Circuits are the measure of production for logic products.

chemical usage at the facility. Chemicals are released to the production floor on an as-needed basis. Little chemical inventory is held in production areas except for some maintenance and photo-resist chemicals. Since little inventory is held on the production floor in production tools or in storage, monthly chemical withdrawals are a good proxy for monthly chemical use at the IBM Burlington facility.

IBM provided RTI with 2 years of data on monthly waste generation for a waste stream known as PGMEA/cyclohexanone, and 1 year of data for their general solvents waste stream. Since the analytical method requires more than 12 data points, we were unable to use the general solvents data. Other waste data were also judged to be inappropriate for this analysis because they provided information about waste inventory rather than waste generation.

IBM's chemical waste data are tracked in the hazardous-waste storage and shipping area where monthly inventory records are maintained.

Production Data. IBM provided researchers with monthly data for the number of modules and monthly data for bits and circuits. In addition, the company provided information about the percentage revenue attributable to these products.

4.3.2 Data Analysis

Analyses were performed on chemical use data and the PGMEA/cyclohexanone waste stream data using four possible units-of-product: IBM's performance index, bits, circuits, and millions of modules. Analyses for isopropyl alcohol (IPA) use and PGMEA/cyclohexanone waste stream are presented in the following sections. Summary results of analysis of the seven chemical uses and the one waste stream following the detailed analyses are presented later on page 57 (Table 4-8).

IPA Analysis. The histograms of IPA use adjusted by the performance index (PI) and IPA use adjusted by millions of module parts are presented in Figures 4-30 and 4-31.

Time series plots were also prepared to see the variation in IPA use per unit-of-product over

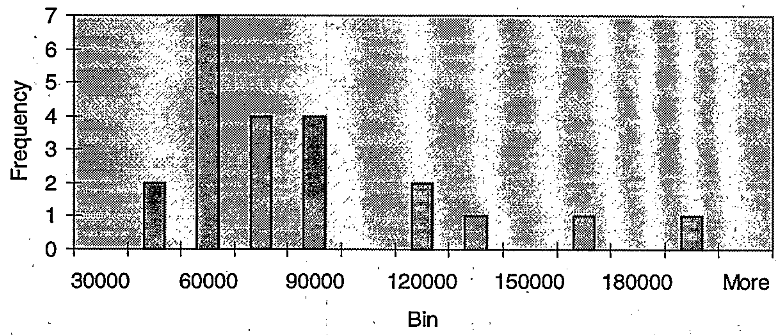

Figure 4-30. Monthly IPA use per performance index unit histogram.

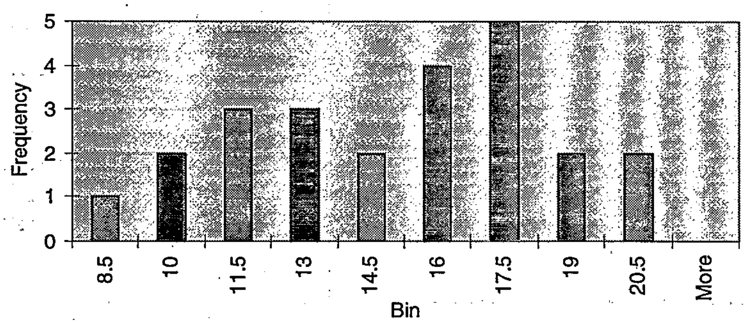

Figure 4-31. Monthly IPA use per million modules histogram.

time. All things being equal, one would expect a random time series pattern—as opposed to an increasing pattern or decreasing pattern.[7] The time series plots in Figures 4-32 and 4-33 have a fairly random order—although a somewhat cyclical pattern emerges in months 13 to 22 in Figure 4-32 (IPA use per performance index unit).

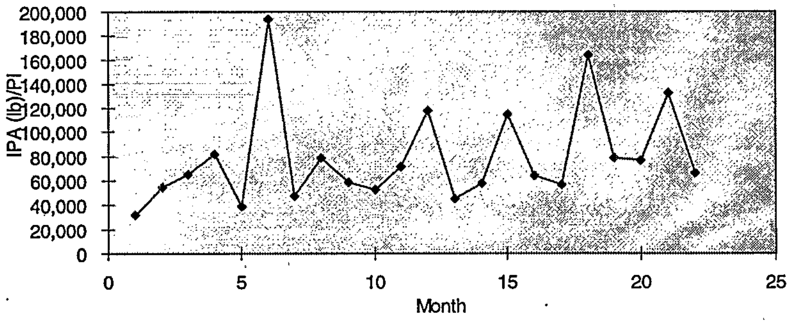

Figure 4-32. Monthly IPA use per performance index unit time series plot.

Lastly, scatter plots of the unit-of-product on the x-axis (performance index and module parts) and IPA use on the y-axis were prepared (Figures 4-34 and 4-35). Best-fit regression lines were added to each scatter plot as were R-squared values and equation for the line. R-squared values closer to 1.0 are indicative of greater correlation.

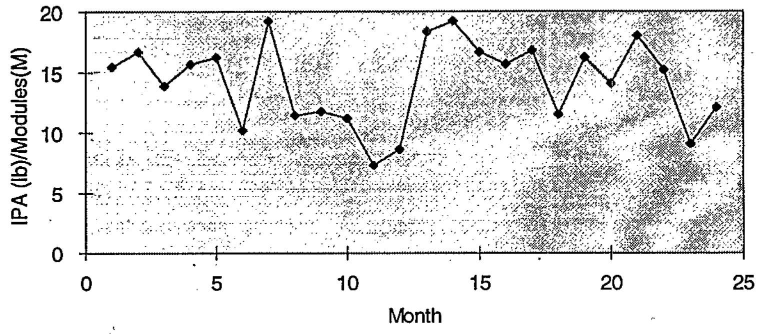

Figure 4-33. Monthly IPA use per million modules time series plot.

The scatter plots and regression lines indicate that IPA use and module parts are better correlated than IPA use and the performance index. The Figure 4-35 linear regressions R-squared statistic equals ~0.58—inferring that the number of module parts produced accounts for 58% of the variation in IPA use. The equation of the line (y = 7,014x + 37,033) indicates that over the 24-month time period 1993-94, the average pounds of IPA use per million module parts equaled 7,014.

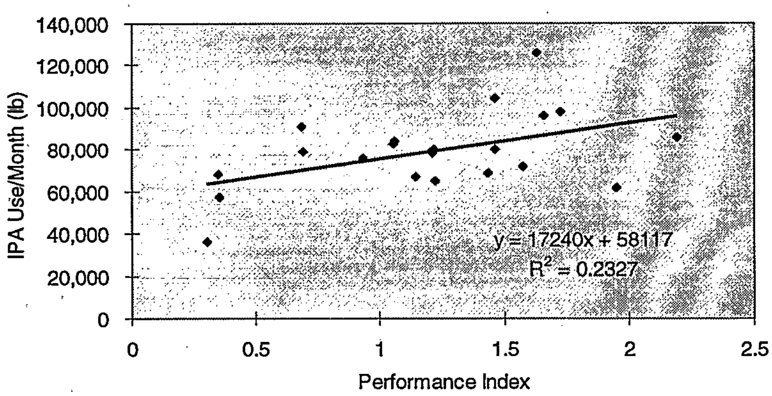

Figure 4-34. Monthly IPA use per performance index unit scatter plot.

[7]Constantly increasing or decreasing trends are indicative of unstable processes. It would be next to impossible to find a correlated unit-of-product for an unstable process.

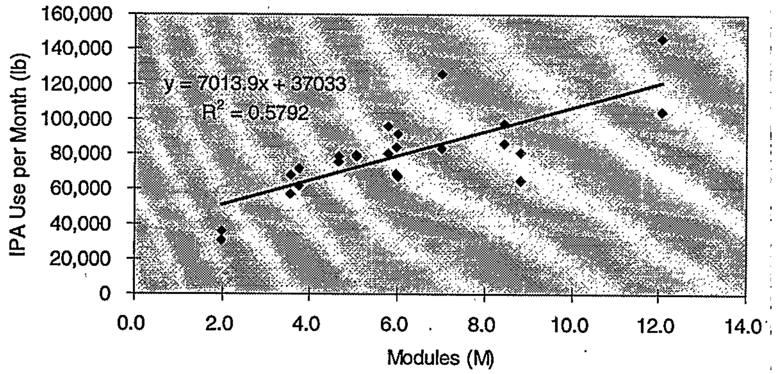

Figure 4-35. Monthly IPA use per million modules scatter plot.

We ran regression tests on the component parts of the IBM performance index to see if either bits or circuits alone were correlated with IPA use. The tests showed that while bits were correlated, circuits were not (Table 4-6). Because bits and circuits are weighted together using percent revenues at the Burlington plant, the lack of circuit correlation negatively affects the correlation between the performance index and IPA use.

In summary, module parts have a stronger correlation than the performance index to IPA usage. Of the two performance index components, only bits were strongly correlated to IPA use over the 24-month time-frame 1993–1994.[8] Depending on site conditions at IBM Burlington, the analysis results for IPA usage could be proxies for the correlations (or lack thereof) for IPA waste streams.

PGMEA/Cyclohexanone Waste Stream Analysis. Graphical methods were also used to examine the potential correlation between PGMEA/cyclohexanone waste stream data and different units-of-product. Histograms of monthly PGMEA/cyclohexanone waste (in pounds) per performance index and per million modules are presented in Figures 4-36 and 4-37. Note that neither histogram has a bell-shaped appearance. In addition both histograms appear skewed and have extremely high values—an early warning that correlations for both units-of-product are likely to be weak.

Time series plots were also prepared to see the variation in PGMEA/cyclohexanone waste stream per unit-of-product over time. All things being equal, one would expect a random time series pattern—as opposed to an increasing pattern or decreasing pattern. The time series plots in Figures 4-38 and 4-39 have a fairly random pattern.

Scatter plots of the unit-of-product on the x-axis (performance index and modules) and the waste stream on the y-axis were also prepared (Figures 4-40 and 4-41). Best-fit regression lines were added to each scatter plot as were R-squared values and an equation for the line.

The scatter plots and regression lines indicate that neither the performance index nor module parts correlate with the PGMEA/cyclohexanone waste stream generation. Both R-squared values are below 0.1 and neither P-value was <0.05. The regression test on bits and circuits data produced similar results—neither was correlated to the PGMEA/cyclohexanone waste stream. One possible source of error in the analysis is that all of the unit-of-product data were registered on the IBM calendar while waste inventory was tracked on a standard calendar.

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[8]It is worth pointing out here that circuits were not correlated to any of the eight chemicals nor to PGMEA waste. This result is discussed in detail later in this report.

Table 4-6. Results of Regression Analysis for IPA Use

	IPA (lb) vs. Bits (trillions)	IPA (lb) vs. Circuits (millions)
Equation of line	y = 1,389x + 51,645	y = 175x + 61,051
R-squared value	0.4989	0.0974
P-value	0.0001	0.13765

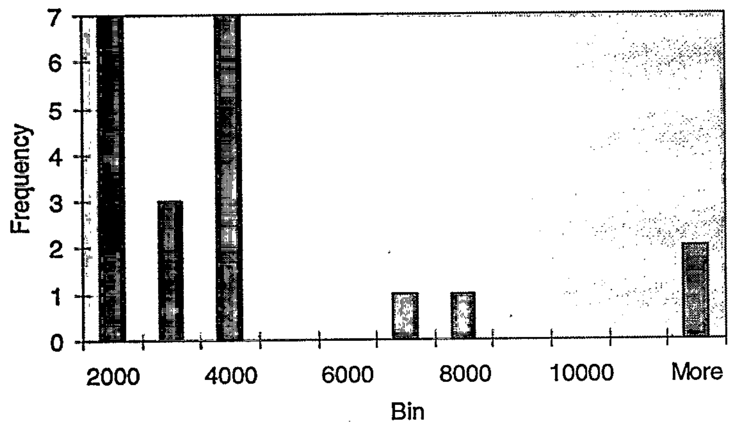

Figure 4-36. Monthly PGMEA/cyclohexanone waste per performance index unit histogram.

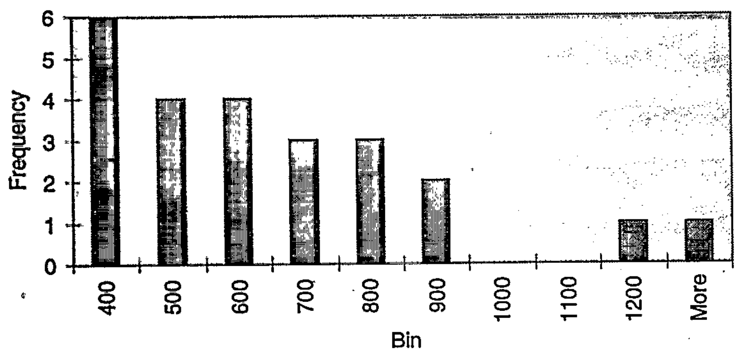

Figure 4-37. Monthly PGMEA/cyclohexanone waste per million modules histogram.

Based on prior work analyzing units-of-product, RTI and Greiner Environmental thought that a time-related function might be at work in the data. Because the waste generated during the manufacture of a given batch of modules, bits, or circuits was likely to enter the waste inventory storage room sometime after actual manufacturing, we chose to represent this time delay by adjusting the waste data by a single month. For example, rather than using the January modules information and January PGMEA/cyclohexanone information as a data pair, RTI decided to use January modules with February PGMEA/cyclohexanone data. IBM Burlington staff agreed that such a move was a reasonable approximation of site conditions.

Histograms of delayed monthly PGMEA/cyclohexanone waste (in pounds) per performance index and per million modules

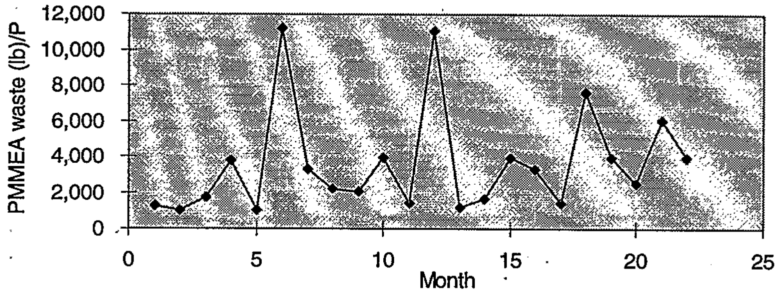

Figure 4-38. Monthly PGMEA/cyclohexanone waste per performance index unit time series plot.

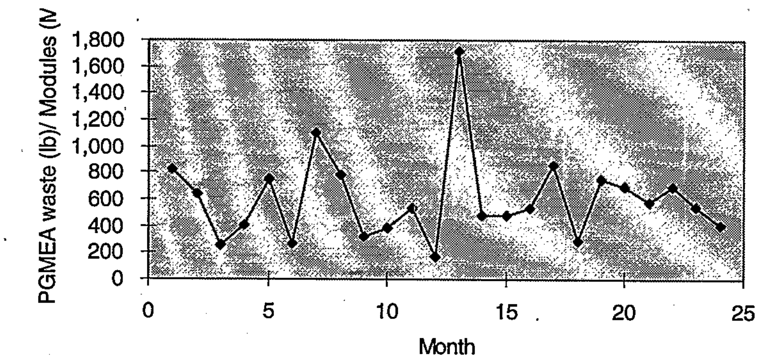

Figure 4-39. Monthly PGMEA/cyclohexanone waste per million modules time series plot.

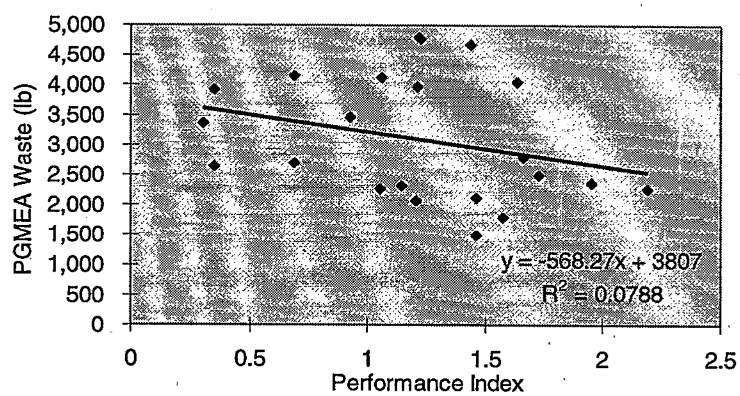

Figure 4-40. Monthly PGMEA/cyclohexanone waste per performance index unit scatter plot.

are presented in Figures 4-42 and 4-43. Both histograms appear bell-shaped—a sign that correlations may have improved due to the delay function.

Time series plots were also prepared to see the variation in delayed PGMEA/cycloexanone waste per unit-of-product over time. As in the prior PGMEA/cyclohexanone plots without a delay function, the time series plots of delayed waste exhibit a random pattern (Figures 4-44 and 4-45).

Finally, scatter plots of the unit-of-product on the x-axis (performance index and million modules) and PGMEA/cyclohexanone on the y-axis were prepared (Figures 4-46 and 4-47). Best-fit regression lines were added to each scatter plot as were R-squared values and equation for the line.

The scatter plots and regression lines indicate that only module parts are significantly correlated to delayed PGMEA/cyclohexanone waste (R-squared = 0.48; P-value = 0.0002). The performance index was not correlated with delayed PGMEA/cyclohexanone waste (R-squared = 0.04, P-value = 0.40). Researchers ran regression tests on the component parts of the IBM performance index to see if either bits or circuits alone were correlated with delayed PGMEA/cyclohexanone waste. The tests showed

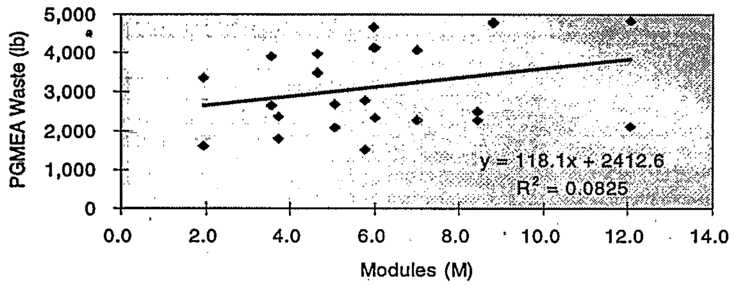

Figure 4-41. Monthly PGMEA/cyclohexanone waste per million modules scatter plot.

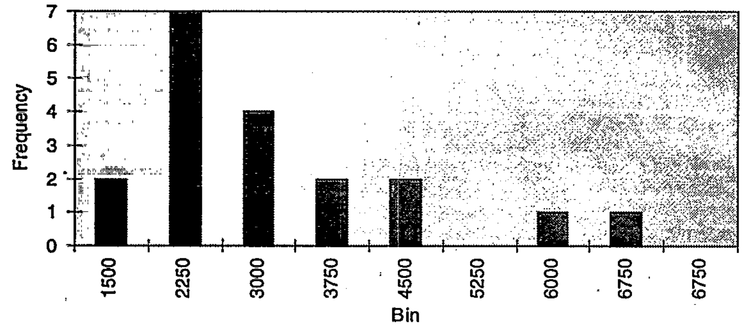

Figure 4-42. Monthly PGMEA/cyclohexanone waste per performance index unit histogram.

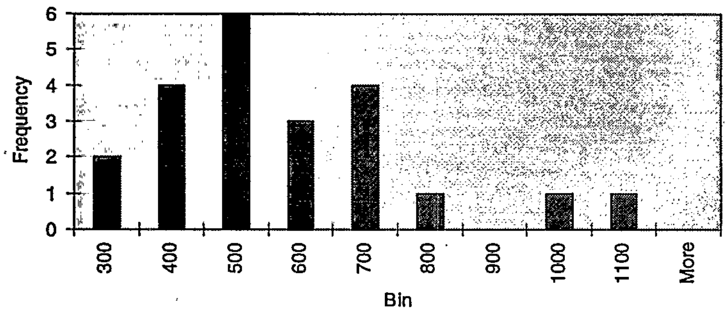

Figure 4-43. Monthly PGMEA/cyclohexanone waste per million modules histogram.

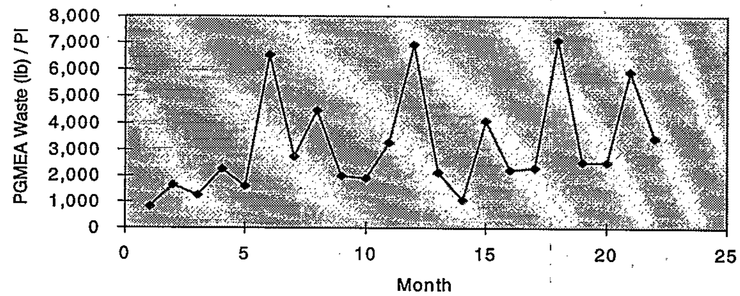

Figure 4-44. Monthly PGMEA/cyclohexanone waste per performance index unit time series plot with 1 month delay.

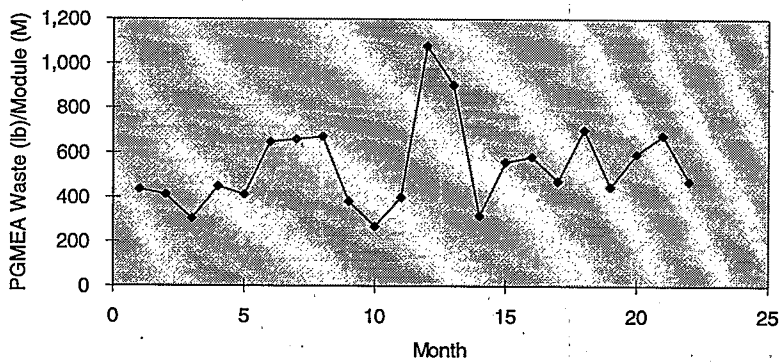

Figure 4-45. Monthly PGMEA/cyclohexanone waste per million modules time series plot with 1 month delay.

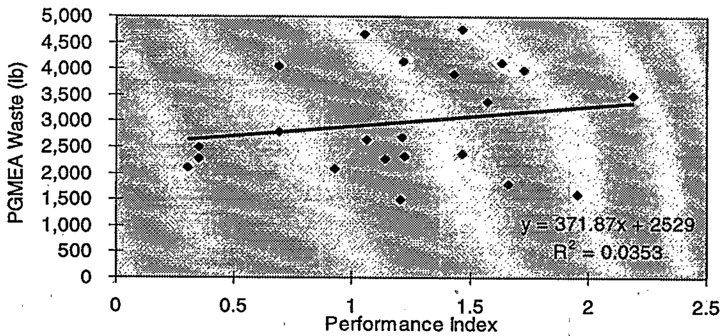

Figure 4-46. Monthly PGMEA/cyclohexanone waste per performance index unit scatter plot with 1 month delay.

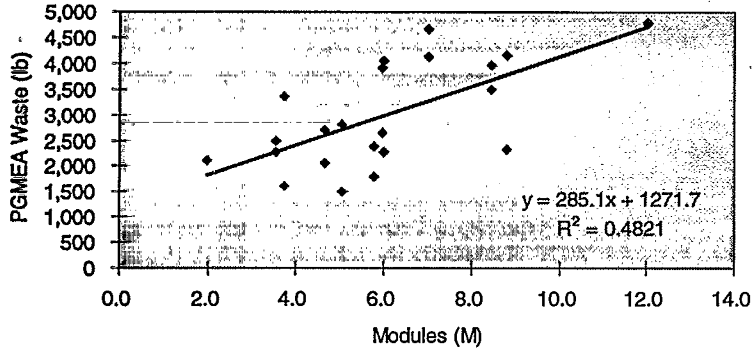

Figure 4-47. Monthly PGMEA/cyclohexanone waste per million modules scatter plot with 1 month delay.

that while bits were significantly correlated, circuits were not (Table 4-7). Since bits and circuits are weighted together using percent revenues at the Burlington plant, the poor circuit correlation has a negative effect on the overall correlation of the performance index.

Thus, only by delaying PGMEA/cyclohexanone waste by 1 month were researchers able to find a correlated unit-of-product. Bits, a component of the performance index, also correlated with delayed PGMEA/cyclohexanone waste, but neither the performance index itself nor the circuits exhibited any significant linear relationship.

Analysis of Other Chemicals. Researchers ran analyses on all of the chemicals listed in Table 4-5. Table 4-8 presents a summary of these analyses. The top number in each cell represents a linear regression R-squared statistic. Values closer to one indicate greater correlation. The lower number in each cell represents a regression P-value. The P-value determines whether or not the correlation between the unit-of-product and chemical are statistically significant. P-values <.05 indicate a statistically significant correlation. The lower the P-value (e.g., P<.001), the stronger the correlation. In most cases, those cells with high R-squared values also have statistically significant P-values. The text in cells with statistically significant P-values have been highlighted to make the chart easier to read.

Examining the chart, one can make the following observations:

- The strongest correlations were seen where modules was used as the unit-of-product;
- Circuits did not correlate with chemical use or waste data;

Table 4-7. Results of Statistical Analysis for PGMEA/Cyclohexanone Waste (Delayed)

	Delayed PGMEA waste (lb) vs. Bits (trillions)	Delayed PGMEA waste (lb) vs. Circuits (millions)
R-squared value	0.36	.005
P-value	0.002	0.75

Table 4-8. R-Squared and P-Values for Chemical Use per Unit-of-Product[a]

	BITS (T)	CIRCS (B)	Per Index	Modules
IPA	**0.50** **<.001**	0.09 >.05	**0.23** **<.05**	**0.57** **<.001**
Ethylbenzene	**0.47** **<.001**	0.04 >.05	**0.23** **<.05**	**0.57** **<.001**
PGMEA	**0.47** **<.001**	0.07 >.05	**0.30** **<.01**	**0.58** **<.001**
Cyclohexanone	0.19 >.05	0.01 >.05	0.08 >.05	0.28 >.05
NBA	0.03 >.05	0.03 >.05	0.04 >.05	0.18 >.05
NMP	0.02 >.05	0.02 >.05	0.04 >.05	0.01 >.05
Xylene	**0.47** **<.001**	0.08 >.05	0.01 >.05	**0.32** **<.01**
Total of seven chemicals	0.04 >.05	0.05 >.05	0.13 >.05	0.22 >.05
PGMEA/cyclohexanone waste	0.04 >.05	0.09 >.05	0.08 >.05	0.05 >.05
PGMEA/cyclohexanone waste (1 mo delay)	**0.36** **<.01**	0.02 >.05	0.04 >.05	**0.48** **<.001**

[a] Summary of analysis chemicals listed in Table 4-5. The upper number in each cell represents the R-squared statistic. The lower number in each cell represents a regression P-value. The text in cells with statistically significant P-values are in bold type.

- PGMEA/cyclohexanone waste data without the delay function did not correlate with any of the four units-of-product; and
- PGMEA/cyclohexanone waste data correlated with bits and modules when waste data were delayed 1 month from production data.

4.3.3 Findings

A number of factors influenced the results of the IBM data analysis. These factors made it likely that that analysis would not detect a correlation between the performance index and chemical use or chemical waste, regardless of whether such a correlation was actually present.

After conducting the analysis, RTI and Greiner Environmental discussed the results with IBM staff. It became clear that, while the data seemed to be time-consistent,[9] they were not. The issues with individual data sources are detailed below. This lack of consistency resulted in a lack of confidence in the results of the analysis.

- The analysis assumed that the production data referred to the quantity of product produced at the facility, rather than the quantity of product shipped. This was an erroneous assumption. The bits, circuits, and modules may have been stored in inventory as long as 2 months before being shipped. Therefore, the information about quantity of product is less related to the use of chemical or generation of waste than it would be if the production data referred to the quantity of product coming out of the production line in a given month.

- It was discovered that the revenue data used to construct the performance index was derived from revenue at the time the product was shipped from inventory. Thus, when we constructed a monthly performance index for purposes of this analysis, the revenue data were not time consistent with production data, making it less likely that any existing correlation would be found. Note that IBM does not use a monthly performance index, but rather constructs an annual index for its P2 report.

- Once it was determined that the figures relating to production referred to products coming out of inventory, it became clear that products shipped in month 2 would likely be responsible for waste generated in *previous* months (i.e., when that product came off the production process). Thus, the analysis that was run to assess the correlation between production and PGMEA/cyclohexanone waste with a 1-month time lag should have actually been run with a 1-month time lag on the production data.

- The production cycle for IBM bits and circuits complicated the analysis process. It takes approximately 3 months to go from components to a finished product. Therefore, it was very difficult to associate a given batch of product with a given quantity of chemical usage or waste generation. Thus it is possible that we failed to detect correlations that are actually present in the manufacturing environment.

- After applying a 1-month delay function to the waste data, we found a correlation between PGMEA/cyclohexanone waste and bits. However, IBM staff reviewing the results report that these two variables should not be correlated, since production of bits does not generate a discrete PGMEA/cyclohexanone waste. A counterintuitive result such as this indicates that there may be other indirect relationships between the waste and the product. It may also indicate a false positive result.

- When these data were collected, IBM was using its own internal calendar. The calendar allocates as few as 14 and as many as 49 days to the 12 months of the year (for example, there are 14 days in January, 28 in February, 35 in March, and 49 in December). Since both production and chemical use data were tracked using the same calendar, the calendar should not impact on the

[9]Section 2.2 of this report explains that the data for the statistical and graphical tools must be time consistent. That is, the waste or use data must correspond to the same time period (e.g., daily chemical use and daily widget production).

data analysis. We confirmed this by examining the data using both the IBM calendar and a standard calendar.

However, waste data are tracked on a standard calendar rather than the IBM internal calendar. The difference between the calendar on which waste is tracked and the calendar on which production is tracked make it difficult to match chemical use or waste with its associated production. IBM no longer uses a nonstandard internal calendar.

These problematic issues illustrate some key points about verifying accurate units-of-product:

- Staff who are doing the analysis must understand clearly the sources of the data they examine. This requires an emphasis on communication between the staff conducting the study and the staff of the facility that provides the information.
- Data must be carefully assessed in light of the requirements of the statistical and graphical tool use methodology, described in Section 2.2 of this report.
- Assessing a unit-of-product is an iterative process. If the analysis provides a counter-intuitive result, then this is an indication that the data sources should be reassessed, as well as the unit-of-product. Depending on how important it is to get an accurate unit-of-product, staff may want to test out more than one unit-of-product and more than one source of data.

4.4 Wyeth-Ayerst Analysis

Wyeth-Ayerst conducted its own data analysis for the unit-of-product used to measure P2 for production of a major pharmaceutical product, referred to here as "product X" at their Rouses Point, New York, facility. Confidentiality concerns were the impetus behind Wyeth's desire to handle production data in-house. They followed the four-step analysis procedure, presented in Section 2 of this report, and worked with Greiner Environmental and RTI to complete the analysis. Thus, Wyeth provided a "field test" of the methodology outlined in this report.

This particular production line was selected for analysis because it is the major hazardous-waste producing process at Rouses Point. We elected not to examine the nonrecurring pilot plant operations at the facility due to resource constraints. Nonrecurring operations present a particularly difficult challenge for evaluation unit-of-product and adjusted P2 measurement. The challenge arises from the fact that nonrecurring operations tend to generate waste and use chemicals in a way that may be unique to each given operation. For instance, a chemical development pilot plant may make a batch of clinical trial material and not make that compound again or it may make it at some time in the future. The chemical development activities typically involve many different chemical inputs, batch sizes and other variables. This results in varied types and quantities of waste per unit input and output.

4.4.1 Process Description/Prepare Process Flow Chart

Product X is produced in two independent process lines at Rouses Point. The process consists of wet granulation steps, drying, and compression into tablets. The final step in the process is product inspection. The quantity of raw materials incorporated into each batch varies according to the dosage of active ingredient for that batch (i.e., if the final product will be an x milligram dose pill, the quantities of raw materials used in that batch are different than if the final product will be a y milligram dose pill).

4.4.2 *Identify and Collect Data*

RTI and Greiner Environmental worked with Wyeth-Ayerst staff to identify waste streams and chemicals used in the pharmaceutical products process that would be suitable for analysis. Because the objective was to test the accuracy of the unit-of-product used to adjust P2 measures for the entire product line (kilograms of product), we tried to identify a material that was used in a way that did not vary dramatically for different batches of the product. It was also necessary to find materials and a waste stream for which data were already collected in an accessible form.

Chemical Waste Data. The most easily available waste data are through monthly shipping records maintained as part of the facility's hazardous waste management system. Those figures, however, were calculated as truckloads of waste and, therefore, did not accurately reflect the amounts of waste generated in the prior month. Originally, plant personnel thought that they would not be able to obtain data about hazardous waste from the individual production lines. However, persistent investigation revealed that such data were being collected by the Technical Services Department for an unrelated special project. These data may not be available for future analyses.

Chemical Use Data. In order to avoid having to make separate calculations for each batch of different formulation product, we chose to analyze use of a solvent mixture ("wetting agent"). This mixture is used as part of the granulation wetting process, and therefore the quantities used are not dependent on which formulation of product X is being produced in a given batch. As described earlier, data about wetting agent usage were found in records collected by the Technical Services Department for a special project.

Unit-of-Product Data. Wyeth's P2 performance tracking system uses kilograms of product as the unit-of-product by which they adjust P2 measurements for product X production. Data showing weekly kilograms of product produced were obtained from the Technical Services Department.

Data Entry. Weekly data from 1996 were entered in spreadsheets by facility staff as follows:

- Solvent mixture (wetting agent) waste generated,
- Solvent mixture (wetting agent) used, and
- Kilograms of product produced.

4.4.3 *Graphical Analysis*

Histogram and Descriptive Statistics. Histograms were prepared for chemical use data and waste data (Figure 4-48 and 4-49). The histograms show that chemical usage and waste generation are normally distributed. There are no significant outliers that would indicate data-collection inaccuracies or irregularities.

Plot Time-Series and Moving Average. Wyeth generated time series plots of wetting agent use per kilogram of product and waste generation per kilogram of product (Figures 4-50 and 4-51). These are used to show trends and cycles in the data. In both cases, the time series plots show random data trends. This indicates a process undergoing normal day-to-day variation. Therefore, the data are suitable for statistical analysis.

Prepare Scatter Plot Diagram. Scatter plot diagrams were prepared for chemical use and

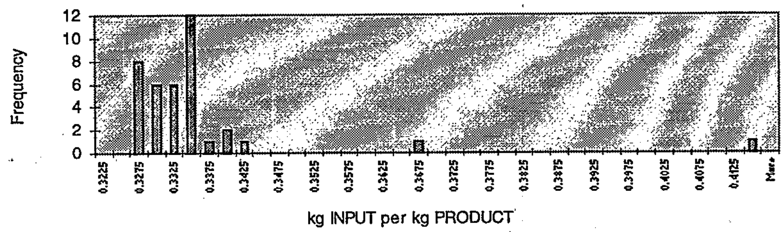

Figure 4-48. Solvent mixture use (kg) per kilogram of product histogram.

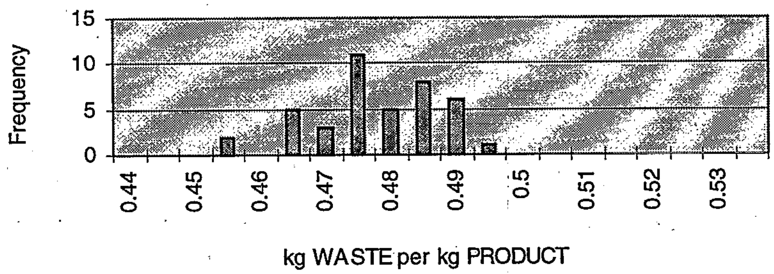

Figure 4-49. Waste production (kg) per kilogram of product histogram.

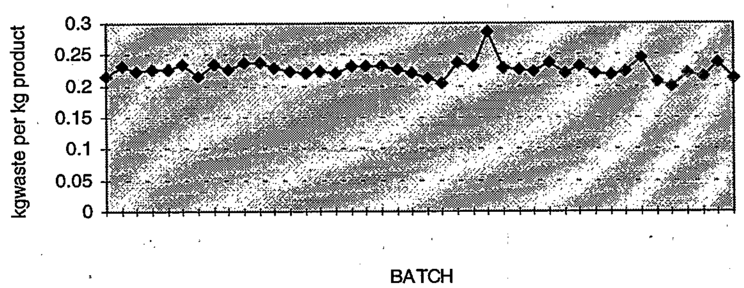

Figure 4-50. Waste per product (kg) per kilogram time series plot.

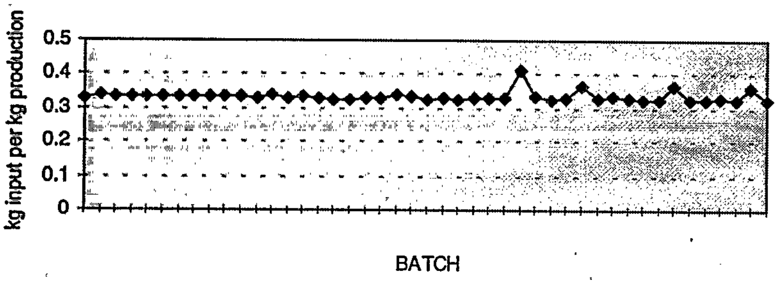

Figure 4-51. Chemical use per product (kg) per kilogram time series plot.

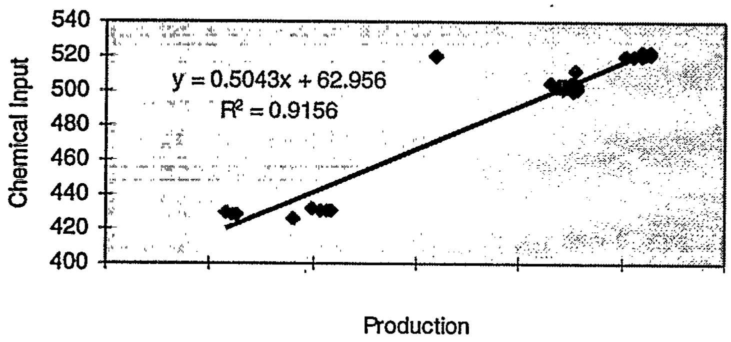

Figure 4-52. Production vs chemical use scatter plot.

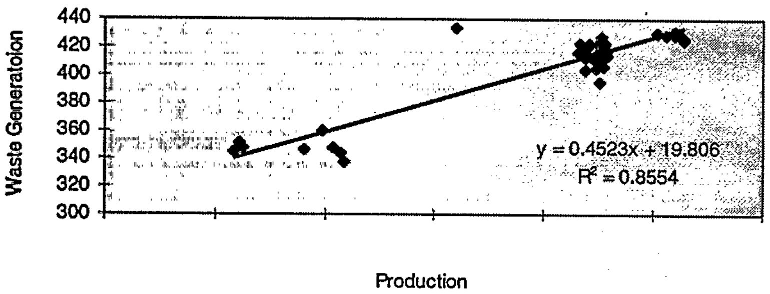

Figure 4-53. Waste production (kg) per kilogram of product scatter plot.

chemical waste (Figures 4-52 and 4-53). The scatter plots show increasing relationship between chemical use and production as well as between waste generation and kilograms of production. It was clear that it would be easy to fit a line to the data. This indicated that kilograms of product are a good unit-of-product to use in adjusting measures of P2.

4.4.4 Statistical Analysis

Wyeth ran regression tests on the data for chemical use vs. production and waste generation vs. production. Since the scatter plots clearly indicated that there was a straight-line correlation between these, the regression tests were something of a formality. The results are presented in Table 4-9.

4.4.5 Findings

Wyeth uses "kilogram of product produced" as the unit-of-product to create a production-adjusted measure of P2 for its production lines. The firm thus calculates change in hazardous waste per kilogram of product produced to use in assessing P2 progress. The analysis method presented in Section 2 of this report, and applied by Wyeth's staff, indicates that the unit-of-product used by the Rouses Point facility is well-correlated with hazardous waste production from a major production line at the facility.

In addition, the analysis showed that there is a correlation between the quantity of wetting agent solvent mixture that is used and kilograms of product X produced. This correlation allowed Wyeth to identify usage of wetting agent as another potential P2 progress indicator.

Table 4-9. Results of Regression Analysis for Waste and Chemical Use per Unit-of-Product

	Waste per kg product	Wetting agent use per kg product
Equation of line	y = 0.4523x + 19,806	y = 0.5043x + 62.956
R-squared value	0.8554	0.9156
P-value	0.000	0.000

They also were able to use the Section 2 methodology to identify another potential P2 progress indicator—usage of wetting agent.

4.5 Results of Statistical and Graphical Analysis on Data from Erving Paper, Erving, Massachusetts

Erving provided us with data on usage of caustic and bleach for this analysis. The information came from Erving's daily process control data-collection process. During a site visit in January 1996 to the company's Massachusetts facility, Erving Paper provided chemical use and production data from the company's Massachusetts paper manufacturing facility. The data were analyzed to determine whether sulfuric acid, caustic, and bleach usage (chemical data) are correlated with paper production. Tons of paper produced is the unit-of-product that Erving uses to adjust its P2 measurements. Erving Paper staff expected that usage of all three chemicals is strongly related to the level of paper production.

4.5.1 Process Description

The continuous manufacturing operations at the Massachusetts facility use a variety of acids, bases, and paper finishing chemicals to produce its products (Figure 4-54). We examined the correlation between production and the use of three process chemicals. Caustic or sodium hydroxide is added to a wet paper slurry to raise its pH; bleach or sodium hypochloride is added as a de-inking or whitening agent; and sulfuric acid is added to lower the wet paper slurry pH to 7.5.

4.5.2 Data Collection

Erving Paper measures the majority of its chemical use daily—taking readings each weekday morning at 7 a.m.

4.5.3 Data Analysis

We analyzed Erving's P2 measurement data to determine whether chemical use and paper production were correlated. Analysis for each of the three chemicals is presented below.

Caustic (Sodium Hydroxide). There was abnormally high use of caustic recorded each Monday. This results from the way data are collected: Monday data points represent 3 days of production (Friday at 7 a.m. to Monday at 7 a.m.). The time series plot (Figure 4-55) shows this pattern (notice the data peaks every fifth data point).

We therefore removed Mondays from the data set and examined chemical use and production for Tuesday through Friday data (Figure 4-56). Removing the Monday data eliminated the pattern noted above.

Next, we prepared a scatter plot and linear regression of the Tuesday-Thursday data. Although one would expect caustic use and paper production to be correlated, a scatter plot of the data depicts no such correlation. The simple linear regression generated an R-squared value

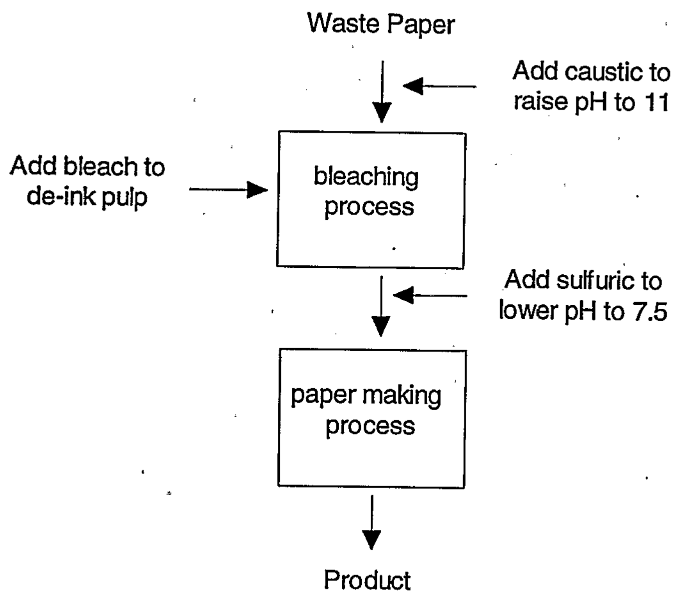

Figure 4-54. Paper production process at Erving paper.

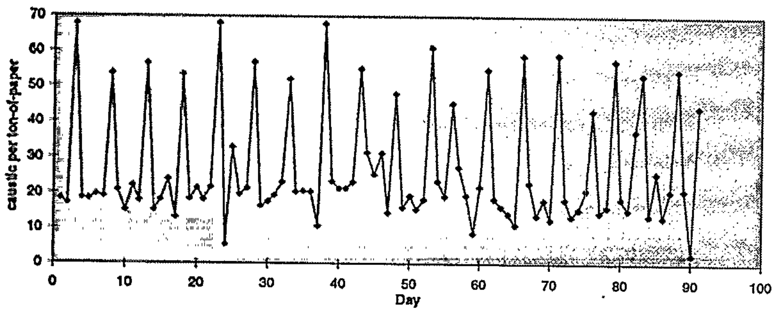

Figure 4-55. Daily caustic use (lb) per ton of paper produced time series plot.

equal to .01—meaning that caustic use described only 1% of the daily variation in paper production (Figure 4-57).

However, closer examination of the data revealed several abnormalities that indicate probable data-collection errors. These abnormalities include the following:

- On several days caustic use per ton of paper was uncharacteristically low. These days were followed by days with uncharacteristically high caustic use per ton of paper.
- On several days when deliveries were accepted to fill the caustic bulk tank, caustic use per ton of paper was uncharacteristically high or low given the level of production.
- A lack of caustic measurement resolution may introduce a significant variability into the data. This variability would make it difficult to observe a relationship between daily caustic use and daily production.

To minimize these ambiguities, we conducted the analysis using weekly data (as opposed to daily data). Weekly data have the advantage of smoothing out these measurement problems. Using weekly data, a time series plot, histogram plot, and a scatter plot were prepared. The time series plot (Figure 4-58) depicts a process undergoing normal variation as opposed to exhibiting a consistently increasing or decreasing pattern.

The histogram of caustic per ton of paper (Figure 4-59) has a bell-shape, again indicating normal process variation.

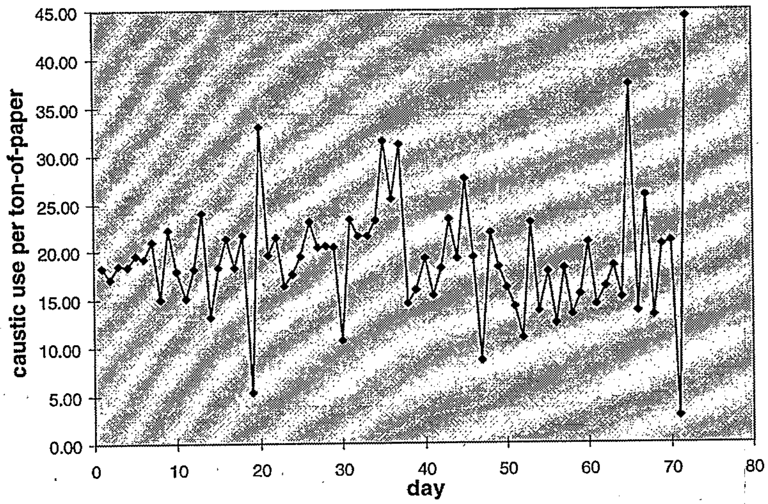

Figure 4-56. Daily caustic use (lb) per ton of paper produced time series plot with Monday data removed.

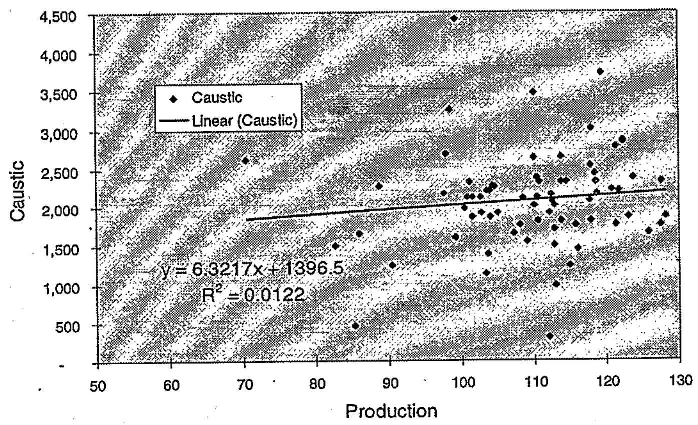

Figure 4-57. Daily caustic use (lb) per ton of paper produced scatter plot.

A simple linear regression generated an R-squared statistic equal to 0.6269—inferring that the level of paper production accounts for 62.7% of the variation in caustic use (Figure 4-60). The equation of the line (y=25.531x - 5090.6) indicates that the average pound of caustic used per ton of paper equals 25.53. The three data points (in Figure 4-60) showing the lowest weekly caustic use are especially significant in the regression. These data points represent weeks with holidays (Thanksgiving, Christmas, and New Years). Were these data points removed from the data set, the relationship between caustic use and paper production would not be as apparent.

Sulfuric Acid. Erving Paper's daily sulfuric acid data have many of the same issues as the company's daily caustic data. We ran the same diagnostic checks on the sulfuric acid data that we ran on the caustic data. The diagnostic checks found that the lack of weekend data and the poor precision of chemical use measurement made the use of daily data problematic. However, we found that weekly data could be analyzed.

Using weekly sulfuric acid data and paper production data, a times series plot, histogram plot, and scatter plot were prepared. The histogram of sulfuric acid per ton of paper has a bell shape, again indicating normal process variation (Figure 4-61). The time series plot depicts a process undergoing normal variation as opposed to exhibiting a consistently increasing or decreasing pattern (Figure 4-62).

The scatter plot of production versus sulfuric acid shows an increasing relationship, and a "best-fit" line is easily drawn through the data points (Figure 4-63). This observation confirms Erving Paper's expectation that higher levels of

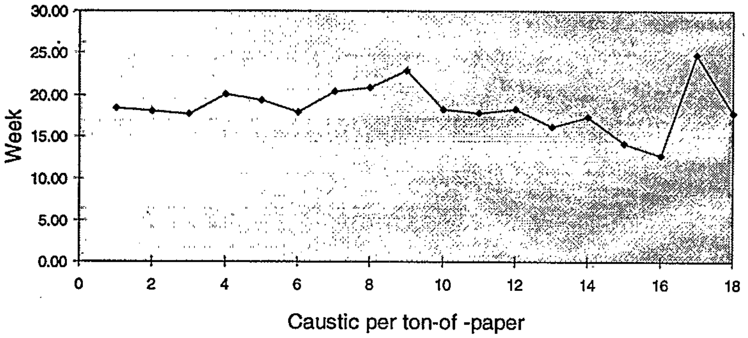

Figure 4-58. Weekly caustic use (lb) per ton of paper produced time series plot.

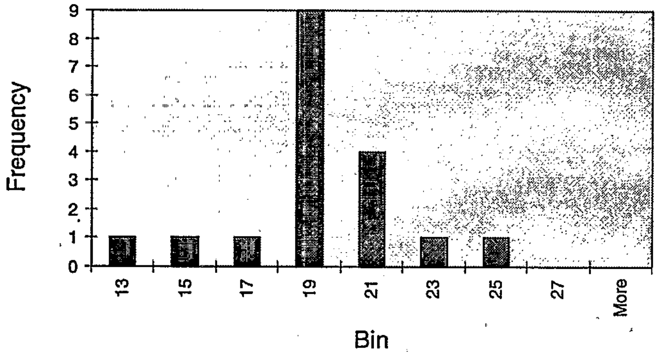

Figure 4-59. Weekly caustic use (lb) per ton of paper produced histogram.

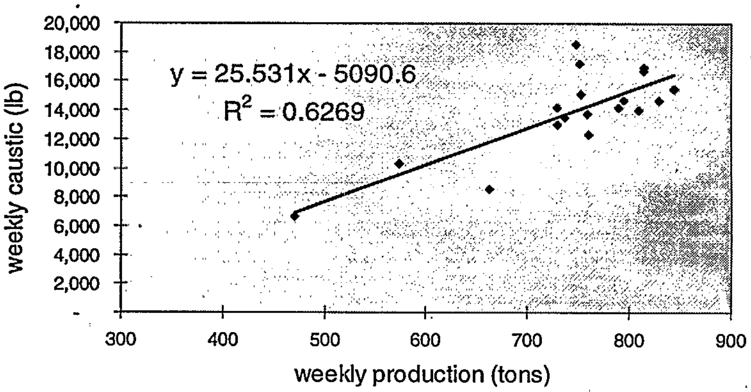

Figure 4-60. Weekly caustic use (lb) per ton of paper produced scatter plot and regression line.

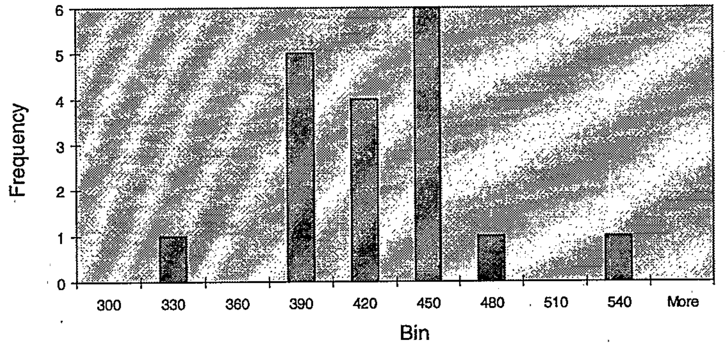

Figure 4-61. Weekly sulfuric acid use (lb) per ton of paper produced histogram.

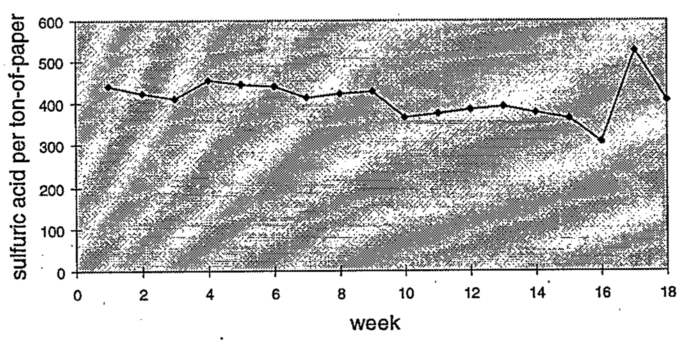

Figure 4-62. Weekly sulfuric acid use (lb) per ton of paper produced time series plot.

sulfuric acid use correspond to higher levels of production.

A simple linear regression produced an R-squared statistic equal to 0.681, inferring that the level of paper production accounts for 68.1% of the variation in sulfuric acid use. The equation of the line (y=504x - 67311) indicates that the average pounds of sulfuric acid used per ton of paper equal 504. As in the caustic case, three data points (in the lower left of Figure 4-63) are especially significant in the regression. These data points represent weeks with holidays (Thanksgiving, Christmas, New Years). If these data points were removed from the set, the relationship between sulfuric acid and paper production would not be as apparent.

In summary, tons of paper produced could serve as a unit-of-product to adjust measures of change in sulfuric acid use. Pounds of caustic used could also serve as a surrogate for production in adjusting measures of change in sulfuric acid use.

Bleach (Sodium Hypochloride). Unlike caustic and sulfuric acid patterns, Erving's bleach data do not display a Monday-spiking effect (Figure 4-64). This was puzzling, since the data are collected at the same times as the other chemical usage data are.

Using daily data on bleach usage, we prepared a scatter plot of daily bleach use versus paper production (Figure 4-65). The plot shows no discernible relationship between bleach use and paper production. The regression R-squared term is equal to 0.0116, indicating that the tons of paper produced explains only 1.16% of the variation in daily bleach use.

In addition to analyzing daily bleach use data, we prepared time series and scatter plots of weekly bleach use and tons of paper. The time series plot (Figure 4-66) is typical of a process undergoing normal process variation.

However, the scatter plot (Figure 4-67) shows no relationship between the two factors. The data are so scattered that no "best-fit" regres-

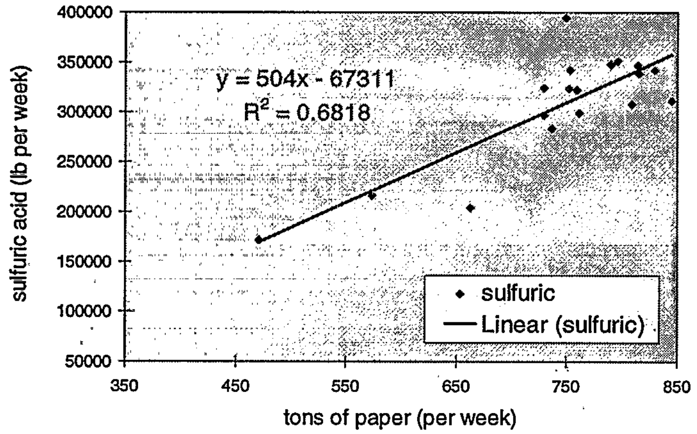

Figure 4-63. Weekly sulfuric acid use (lb) per ton of paper produced scatter plot with regression line.

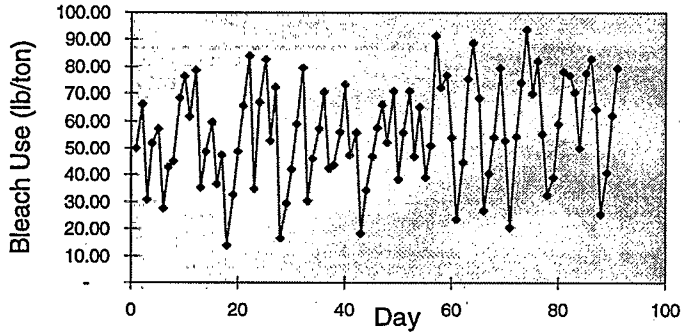

Figure 4-64. Daily bleach use (lb) per ton of paper produced time series plot.

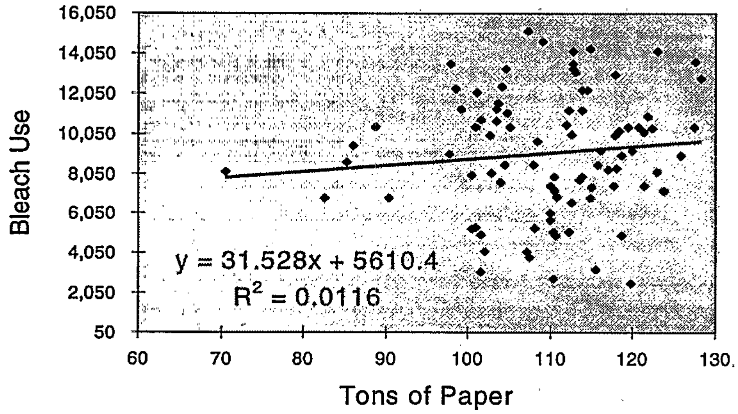

Figure 4-65. Daily bleach use (lb) per ton of paper produced scatter plot with regression line.

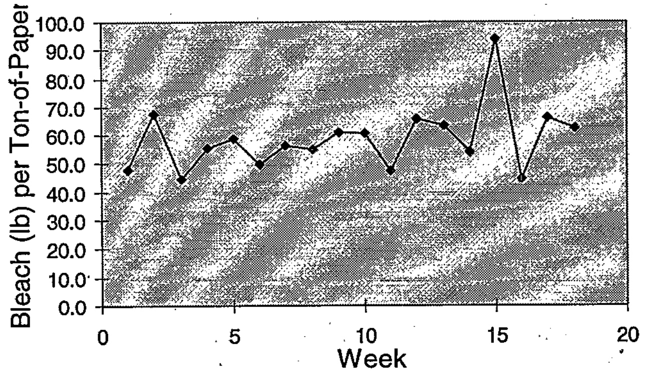

Figure 4-66. Weekly bleach use (lb) per ton of paper produced time series plot.

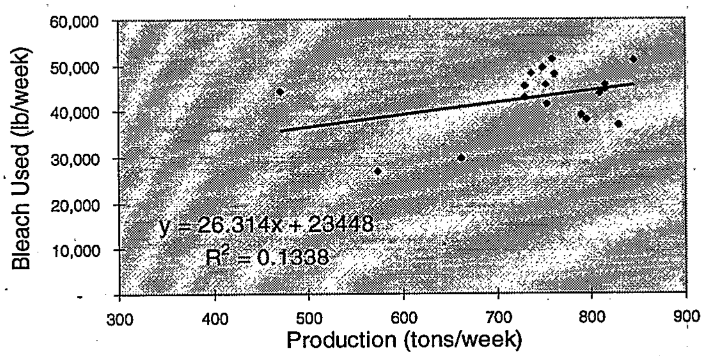

Figure 4-67. Weekly bleach use (lb) per ton of paper produced scatter plot with regression line.

sion line can be drawn with any certainty. The regression term for weekly bleach versus tons-of-paper produced is only 0.1338. This implies that only 13.38% of the variation in the weekly bleach use is explained by variations in production. Regressions examining bleach use versus production on Tuesday through Thursday produced similar results.

4.5.4 Findings

Since 1990, Erving Paper has used tons of paper produced as the unit-of-product to adjust measures of chemical use of the level of production. The present analysis determined that this practice is effective for two major chemical uses (caustic and sulfuric acid) but not for bleach. These two chemicals are good indicators of Erving's P2 progress.

The lack of correlation between bleach use and paper production runs counter to what one might expect. Conventional wisdom holds that bleach usage is directly proportional to tons of paper produced. However, based on this analysis, it would be far better to measure P2 by looking at changes in caustic use or sulfuric acid usage per ton of paper produced. Alternatively, there might be units-of-product at Erving paper that have a stronger relationship with bleach use (e.g., tons of pulp rolled out, or number of boxes shipped).

Section 5
Conclusions

In this research we conducted three tasks:

- Described the use of production-adjusted measures of P2 at five different facilities;
- Developed a method to apply statistical and graphical tools to analyze the accuracy of factors used for production-adjusting P2 measurement; and
- Analyzed the factors used for production-adjusted P2 measurement at five case study facilities.

This section elaborates on conclusions drawn from the results of the three task areas.

5.1 Use of Production-Adjusted P2 Measures

While the major driver for developing production-adjusted measurements of P2 has been regulatory requirements, firms have also found nonregulatory uses for production-adjusted P2 measures. Specific applications include:

- Process control,
- Quality control,
- Internal communications, and
- External communications.

Production-adjusted measures of P2 can be used to assess yearly P2 progress, or they can be generated more frequently to provide insight into day-to-day functioning the process line. This insight can help firms fine-tune their production processes to improve efficiency.

The process of developing and verifying production-adjusted measurements of P2 can be valuable to the facility. The process of identifying monthly or weekly data for a production process provides insight into the kinds of data that are available at the facility for purposes of measurement and for process control. This is a different perspective than that gained while identifying yearly data for reporting purposes.

A dilemma is presented to environmental staff who are selecting indicators of P2 progress. They must either choose to base the measurement on existing data or they must collect new data to feed into the measurement. Collection of new data can take significant resources and may not be a desirable option. But if the measurement is based on existing data, then all future measurements will be dependent on the continued collection of that data. Two of our case study facilities found that collection of some of the data on which they based their measurements was scheduled to be phased out. This experience indicates that it is desirable to obtain institutional support for P2 measurement in order to ensure continued collection of the necessary data.

Measuring P2 can be a resource-intensive process. It is important to ensure that the resources expended are in line with the benefits that are expected. It is counterproductive to spend many staff hours to develop and implement a measurement system if no resources will be left to actually implement P2 projects. Likewise, a P2 measurement system should be selected that is appropriate to the production process or facility being measured: If the process is constantly changing, the measurement system should reflect that. If the product in question is being phased out, then a more rudimentary measurement may be in order.

5.2 Methodology for Verification of Production-Adjusting Units

This research developed a methodology for applying statistical and graphical tools for analyzing units-of-product that allow a facility to assess how well correlated a unit-of-product and a target waste stream or chemical use are. The user assesses this by using tools to calculate how much of the variation in a waste stream or chemical use is due to variation in the unit-of-product. The user also calculates whether this result is statistically significant. If a unit-of-product and target waste stream or chemical use are well correlated, then a P2 measurement using that unit-of-product will accurately reflect production-adjusted P2 for that process or facility.

5.2.1 Assessment of Data

Assessing a production-adjusted P2 measurement system using the tools recommended in this report is an iterative process. In most of the analyses conducted during this research, several attempts were needed to identify data suitable for analysis. Issues that arose during the analysis include the following:

- Accurate monthly or weekly hazardous waste generation data may not be available. Often the available hazardous waste data are from shipping records rather than from the production process. The data may, therefore, reveal more about the schedule of the hazardous waste hauler and the capacity of their trucks than about the generation of waste during a particular period. In cases where waste generation data appear not to reflect production well, chemical use data may be a good substitute.
- Chemical use or waste data may lag behind actual production. In some cases, the available data come from sources that are not directly associated with the production line. Chemical use data may come from withdrawals from inventory. Hazardous waste data may come from transfers to hazardous waste storage. In either of these cases, the data from month 2 may actually have resulted from production in month 1. In these cases, it may be possible to add a delay function in the analysis.
- Data must be verified to ensure that they reflect what the user thinks they are supposed to be showing. For instance, periodic data peaks every Monday in data at the Erving Paper case study (given in Section 4.5) turned out to represent 3 days' worth of data rather than just 1 day of data. Use of a time-series plot should provide insight into data anomalies. These should be followed up with facility personnel to assess the sources of the data.

5.2.2 Using Chemical Use Data to Evaluate Units-of-Product

In many cases during the analysis of units-of-products used by case study firms, RTI and Greiner Environmental worked with chemical usage as an indicator of P2 progress. This occurred in two different situations:

1. In some cases, the facility was using change in chemical usage per unit-of-product as a P2 indicator. The analysis then served to verify whether the unit-of-product that the facility was using was correlated with chemical usage (i.e., served to verify the

existing production-adjusted P2 measure that the facility had in place).

2. In other cases, facilities were tracking waste per unit-of-product but were unable to obtain adequate waste data to conduct an analysis. In these cases, we conducted analyses based on chemical use data. This tested whether variation in chemical usage was correlated with variations in unit-of-product. The results of the analysis provided the firms with information about a potential new production-adjusted indicator of P2 progress (change in chemical usage per unit-of-product). In addition, chemical usage may be a good surrogate for certain waste streams. This is discussed further in the remainder of this section.

   Chemical usage will be a good surrogate for waste generation in situations where the two are strongly related. This will often be true where the chemical is used in a process but not incorporated into the product. If facility personnel determine that this is the case, then a unit-of-product that is correlated to changes in chemical use will also be correlated to change in waste streams for that chemical.

Analysis of Data. Analysis of data to assess the correlation between waste or chemical use data and unit-of-product is not a "black-box" process. It requires extensive communication among firm personnel, from production engineers to accounting staff. Users of the methodology presented in this report must understand the objectives of the analysis and should periodically assess how well the methodology fits the data that are available through the analysis process. Section 4 of this report describes the analysis process for data from the five case study sites. Some of the major issues encountered during these analyses include the following:

- Where weekly data gave indicators of being inappropriate for analysis based on the criteria explained in Section 2, sometimes aggregating the data into monthly data made it more amenable to analysis.
- Where extreme outliers were present in the data, we assessed whether the outlier affected the descriptive statistics for the measurement unit to the point where it could not be used. In that case, the analysis was repeated without the outlier to assess whether the unit-of-product and waste or chemical use were correlated under normal circumstances.
- Where it appeared that data were not time-consistent as required by the methodology, we introduced time lag functions. The time lag is intended to allow the analyst to look for the correlations between a given unit-of-product and the waste or chemical usage actually associated with that batch of product, rather than a batch of product produced in the following or previous month.
- In performing the analysis and working around data issues, it was often necessary to consult with facility and production staff to ensure that the proposed change in the analysis was still consistent with the way the production process is run.

After the analysis was completed, it was reviewed by production staff to ensure that the results were consistent with common sense. Results that seemed counter-intuitive were re-examined for further insights and for accuracy.

5.3 Units-of-Product Used by Case Study Firms

Examination of case study facilities allowed us to examine the workings of five different production-adjusted measurements of P2 in five different industries. These industries use production-adjusted measures of P2 for very different purposes—from process control to stakeholder communication to regulatory requirements. Further, the units-of-product they use in their P2 measurement schemes vary from the simple to the complex.

We found that single units-of-product (like "square feet plated" or "kilograms of product produced") generally correlated well with chemical use and, in some cases, with waste generation. This finding is important because there has been some concern that single units-of-product are inadequate to explain variation in waste generation. If this were true, then it would be much more difficult for firms to accurately assess their P2 performance, since they would have to account for many more variables than a single measurable output. Our results, however, suggest that a carefully chosen single-variable unit-of-product can account for enough of the variation in chemical use or waste to be used in adjusting gross P2 measures.

In other words, we found that there was a statistically significant relationship between a single unit-of-product and chemical usage in all five of the case study facilities. This is somewhat surprising, since complex processes might be expected to have several variables that explain variation in chemical usage (e.g., operational conditions, quantity of product, quality of inputs). However, production levels of a given product affected chemical use enough that a statistically significant linear relationship between the two could be detected.

5.3.1 Larger-Scale Production-Adjusted P2 Measurements

This research investigated only one instance of production-adjusted P2 measurement across multiple product lines. It did not investigate production-adjusted P2 measurement across multiple facilities. Further investigation of how to appropriately aggregate measures of P2 is an important next step in understanding the impacts of efficiency and environmental protection efforts by firms.

Section 6
References

Greiner, Timothy J. 1994-95. Normalizing P2 data for TRI reports. *Pollution Prevention Review*. Winter. pp. 65-75.

Harriman, Elizabeth, Jay Markarian, Jay Naparstek, James Stolecki, and Anne Marie Desmarais. 1991. *Measuring Progress in Toxics Use Reduction*. Department of Civil Engineering, Tufts University. Prepared for Massachusetts Department of Environmental Protection, Boston, Massachusetts. August.

Tellus Institute, Sound Resource Management Corporation, CCA, Inc., and Matrix Management Group. 1991. *P2 Measurement Project: Normalization Measures: A Report to Washington Department of Ecology*. Olympia, Washington. June.

Appendix A
Selected Reports and Articles Dealing with Production-Adjusted Measures of P2

Behmanesh, Nasrin, Julie A. Roque, and David T. Allen. An analysis of normalized measures of pollution prevention. *Pollution Prevention Review*. Spring, 1993, pp. 161-166.

Butler, Craig. Ohio Waste Minimization Measurement Pilot Project: An Analysis of Pollution Prevention Measurement Options for Ohio. Columbus OH: Ohio Environmental Protection Agency, Office of Pollution Prevention, March 1996.

INFORM, Inc., *Toxics Watch, 1995*. New York. 1995.

Malkin, Melissa, Jesse N. Baskir, and Jordan Spooner. Issues in facility-level pollution prevention measurement. *Environmental Progress* 14(4):240-246.

Washington State, Department of Ecology. *Pollution Prevention in Washington State, Task 2: Testing the Utility of Pollution Prevention Measurement Methods and Data at the Facility Level.* Washington State Department of Ecology, Hazardous Waste and Toxics Reduction Program, Olympia, WA, Publication Number 94-191, August 1994.

Appendix B
Selected Statistical Resources

Most basic statistics and data analysis text books review graphical and regression analysis techniques. The three books listed below are good starting points for those wishing to investigate these methods.

Anderson, David R., Dennis J. Sweeny, and Thomas A. Williams. *Introduction to Statistics: Concepts and Applications*. St. Paul, MN: West Publishing Company. 1991.

Box, George E.P., William G. Hunter, and J. Stuart Hunter. *Statistics for Experiments*. New York: John Wiley and Sons. 1978

Hogg, Robert V., and Johannes Ledolteer. *Applied Statistics for Engineers and Physical Scientists*. New York: Macmillian Publishing Company. 1992.

Appendix C
Framework for Production-Adjusted Measurement of P2

Use of production-adjusted measures of P2 can ensure that a facility is measuring emissions or waste changes that are the result of P2 or other factors besides mere fluctuations in production levels. Our case studies also found that the process of setting up a production-normalized measure of P2 can provide valuable insights to facility management and staff.

This appendix provides a "step-by-step" framework for developing normalized P2 measures at the corporate, facility, or process level.

C.1 Production-Adjusted P2 Measurement Framework

This framework asks a series of questions to lead facility staff through the steps needed to select and verify a production-adjusted measure of P2. The framework for production-adjusted P2 measurement, shown in Figure C-1, provides guidance on identifying the overall scope of a P2 measurement system, collecting data, and selecting a unit-of-product with which to adjust the P2 measurement.

This section outlines the questions that a P2 professional would ask as he/she develops or upgrades a P2 measurement system.

Step 1. What is the goal of the P2 measurement?

Is the goal to measure a particular waste stream? Overall facility reduction goals? The answer to this question will provide information about what kind of data is necessary.

For instance:

- "Ours is an extremely large facility. How can we get the individual process engineers to be responsible for pollution prevention for their areas?" → We need data and metrics for each main production area, plus product data for each of these production areas.
- "We have a facility-wide target of reducing waste by 50% in 5 years. How much of that target have we achieved?" → We need data for the chemicals of concern at the facility, plus production data for product from the major production lines.
- "We have reduced our discharges of arsenic to the publicly owned treatment works (POTW), but we're not sure if this is due to P2 efforts or due to drop-off in activity" → We need data on arsenic discharges, plus a unit-of-product related to arsenic discharge.
- "We want to develop an accurate unit-of-product for use in annual reporting under TURA or TRI" → We need information about annual discharge of regulated chemicals plus a unit-of-product that is representative of the entire facility.

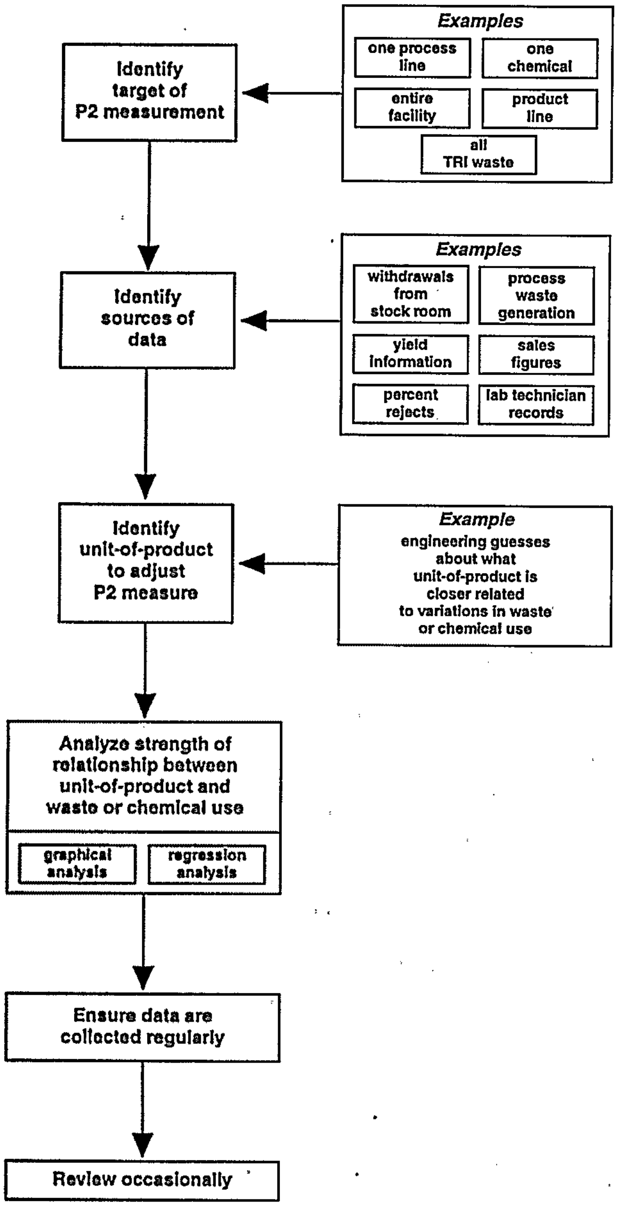

Figure C-1. Framework for production-adjusted P2 measurement.

Step 2. What data are available to answer the questions during the periods in which we want them answered (e.g., daily, weekly, or monthly data for internal measurements; annual data for regulatory reporting purposes)?

Examples of data to measure P2:

- Monthly quantity of waste shipped offsite → Resource Conservation and Recovery Act (RCRA) manifests; hazardous-waste tracking system;
- Periodic quantity of inputs withdrawn from stockroom or otherwise purchased → from accounting department, from quality assurance records;
- Quantity of chemicals added to plating bath weekly → from the lab technicians' records;
- Mass balance or materials balance information → collected during more detailed P2 audits;
- Efficiency data → process engineering;
- Product yield → quality assurance department; and
- Production data → production control department.

Step 3. What units-of-product can logically be used to adjust the P2 measurement to account for production levels?

As described in this report, production-adjusted measures of P2 give a more detailed picture of P2 than gross measures of change in waste or change in chemical use do. At this stage of developing a P2 measure, the facility staff must identify possible units-of-product that can be

Table C-1. Examples of Unit-of-Product Used by Case Study Facilities

Type of operation	Unit-of-product
Metal finishing facility	Square feet of substrate plated
Paper recycling	Tons of paper produced
Electronics production	Number of passes substrate makes through process
Semiconductor fabrication	Combined unit-of-product incorporating bits, circuits, and masks
Pharmaceutical production	Kilograms of product produced

used to adjust measures of P2. The objective is to find those units-of-product that are likely to explain the variation in emissions or chemical use for the facility or process line. Examples from case study facilities are given in Table C-1. Process flow diagrams and conversations with process engineers or line managers can be valuable resources in choosing potential units-of-product.

Step 4. Of the possible units-of-product identified in Step 3, for which are data available?

As described in Section 2, it is preferable to have at least 30 data points in order to verify that the unit-of-product that is chosen is related to the variation in chemical use or waste generation.

At the facilities examined in this research, engineers often found that sources for the data they needed, while not immediately on hand, were typically available. This is because many different data sets are generated at facilities for many different purposes; generally there is not one central place to go for process information. For instance, at one facility, when we first asked the environmental health and safety staff whether weekly production and chemical use data were available, they thought that the information was not available for a single process on a weekly basis. They later found that the information did exist, and they were able to use it to analyze their P2 measurement system.

Where a facility is developing a measure of P2 that measures a full year period, it will obviously be impossible to get 30 data points, each representing the annual measure of P2. For such a measure, the facility should try to find 30 data points for daily, weekly, or monthly data and use these to assess the accuracy of the unit-of-product. If it is found that the unit-of-product chosen explains variation in emissions or chemical use, then the facility can go on and use the available yearly data to construct its annual measures of P2.

Step 5. Which of the possible units of normalization are strongly related to variation in chemical use or waste generation?

Use statistical and graphical analysis to assess the accuracy of unit-of-product options.

Section 2 of this report describes a statistical and graphical method for testing the accuracy of possible units-of-product used at a facility. It is important to test the unit-of-product identified in Step 3 to ensure that it actually explains the variation in chemical use or waste generation. In this step, staff should take the data collected in Step 4 and conduct the statistical and graphical analysis on it. If the unit-of-product is found to explain variation in waste or chemical use, then it should be used in measuring P2.

If the unit-of-product does not explain variation in waste or chemical use, then other units-of-product should be analyzed.

Once a unit-of-product that explains variation in emissions or chemical use is identified, then the facility can calculate the production-adjusted P2 measurement as often as is necessary for their purposes (anywhere from annually for TRI reporting purposes to daily for process control purposes).

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